Role and Application of Accident Modification Factors (AMFs) within the Highway Design Process

by

Dominique Lord
Department of Civil Engineering &
Center for Transportation Safety
Texas Transportation Institute
Texas A&M University System
3135 TAMU, College Station, TX, 77843-3135
Tel. (979) 458-3949
Fax: (979) 845-6481
d-lord@tamu.edu

James A. Bonneson, P.E.
Texas Transportation Institute
Texas A&M University System
3135 TAMU, College Station, TX, 77843-3135
Tel. (979) 845-9906
Fax: (979) 845-6254
j-bonneson@tamu.edu

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ABSTRACT

Over the last few years, there has been a greater emphasis placed by transportation agencies to incorporate safety within the highway design process. The main assumption is that a highway designed with explicit attention to safety could significantly reduce the frequency and the severity of crashes. One tool that is rapidly gaining in popularity is the use of accident modification factors (AMFs) to estimate the change in safety following the implementation of a countermeasure, a significant change in a geometric design element or a planned construction upgrade of a highway facility. Given the fact that AMFs will play a very important role in the coming years, especially with the forthcoming publication of the Highway Safety Manual (HSM), there currently exist no document that addresses how AMFs could potentially be used with the process to design highways. Consequently, there is a need to provide such information so that engineers and highway designers could make the full use of AMFs for this process. This paper describes the role and application of AMFs in the highway geometric design process. More specifically, the paper provides guidelines for applying these factors within the preliminary design stage, for assessing design consistency and for evaluating design exceptions. For each design application, a proposed procedure is described in details. Finally, an example is provided for each design application to better illustrate the description of the procedure.
INTRODUCTION

Over the last few years, there has been a greater emphasis placed by transportation agencies to incorporate safety within the planning and highway design processes. The main assumption is that a highway designed with explicit attention to safety could significantly reduce the frequency and the severity of crashes. As a result of this increasing attention to safety, new tools are currently being developed to incorporate safety within the planning or highway design process \( (1, 2, 3, 4, 5, 6, 7) \). In fact, further evidence of the recognition of the relevance of safety in these processes and of the need for tools to do so is the commissioning of new projects under the National Cooperative Highway Research Program (NCHRP) (NCHRP Project 8-44: Incorporating Safety into Long-Range Transportation Planning and NCHRP Project 17-18(4): Highway Safety Manual).

One tool that is rapidly gaining in popularity is the use of AMFs to estimate the change in safety following the implementation of a countermeasure, a significant change in the geometric design characteristics of a roadway or a planned construction upgrade of a highway section or intersection. In fact, the project NCHRP 17-25 titled “Crash Reduction Factors for Traffic Engineering and ITS Improvements” will provide a series of Crash Reduction Factors (CRFs) that will enable engineers to quantify changes for various traffic engineering, operations, and ITS elements (note: the intrinsic relationship between AMFs and CRFs is discussed in the next section). Given the fact that AMFs will play a very important role in the coming years, especially with the forthcoming Highway Safety Manual \( (8) \) and the recently introduced IHSDM \( (9) \), there currently exists no document that addresses how AMFs/CRFs could be used with the highway design process. Consequently, there is a need to provide such information so that engineers and highway designers could make full use of AMFs for designing highways.

This paper documents the role and application of accident modification factors (AMFs) within the highway design process \( (10, 11) \); an example outlining the highway design process and the key components of the preliminary design stage within this process are illustrated in Table 1 and Figure 1 respectively. The focus of this paper is to summarize the application of AMFs within the highway design process. More specifically, the paper provides guidelines for applying factors within the preliminary design stage, for assessing design consistency and for evaluating design exceptions. For each design application, a proposed procedure is described in details. An example is provided for each design application to better illustrates the concepts describes in the procedure.
Table 1. Stages of the Project Development Process. (12)

<table>
<thead>
<tr>
<th>Stage</th>
<th>Step</th>
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<tr>
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<td>Preliminary Design</td>
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<td>Environmental</td>
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<td>Right of Way Utilities</td>
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<td>9. Traffic Control Plan</td>
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<td>Letting</td>
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The paper is divided into three sections. The first section describes the role AMFs have played in safety evaluation and analysis. The second section describes the three potential applications of AMFs within the highway design process. The last section covers the procedure for applying the AMFs for each application.

BACKGROUND

This section reviews the fundamental principles related to the application of AMFs that describes the relationship between a change in geometry, traffic control device or signalization, and the change in crash frequency associated with the roadway. This review is necessary for describing the procedures in the last section of the paper. Due to space constraint, the topics related to methodological issues and statistical methods used for developing AMFs are not covered in this paper. The reader is referred to Davis (13), Shen and Gan (14), and Bonneson and Lord (15) for a detailed description of these topics.

This section is divided into parts. The first part contains a review about the historic role of crash reduction factors (CRFs) in safety improvement evaluation programs. The second part describes the more recent role of AMFs in highway safety and their relationship with CRFs.

Crash Reduction Factors

CRFs were first developed for the Federal Hazard Elimination Program (HES) (16, 17). In this early application, CRFs were used to estimate the safety effects of improvements in: (1) the geometry of a specific highway segment or intersection, (2) the traffic control devices used on the segment or at the intersection, (3) the signalization used at the intersection, or (4) the roadside clear zone or safety appurtenances. As reported by Shen et al. (18), about 80 percent of state departments of transportation (DOTs) in the U.S. use CRFs to help identify safety improvements for locations with above-average crash patterns.
CRFs have usually been defined in the literature the following way (13, 14, 19, 20):

\[
CRF = 1 - \frac{N_w}{N_{w/o}}
\]  

(1)

where:

\( CRF \) = crash reduction factor associated with a specific improvement;

\( N_w \) = expected number of crashes with the improvement, crashes/yr; and

\( N_{w/o} \) = expected number of crashes without the improvement, crashes/yr.

As suggested by the variable definition in Equation 1, the term “improvement” (or “countermeasure”) is frequently used to describe the change in geometry, traffic control device or signalization. These terms imply the anticipation of a reduction in crashes following the change. When Equation 1 is used to quantify the CRF for a specific improvement, the expected number of crashes with the improvement \( N_w \) is typically estimated as the “number of reported crashes after the improvement \( X_a \).”

Application of Crash Reduction Factors in Safety

CRFs can be used to assess the safety benefit of alternative improvements. This section describes their basic method of application. Initially, it describes the evaluation of a single improvement (or countermeasure). Then, it describes a technique for evaluating several improvements, when all improvements are to be combined into one project.

Safety Effect of One Countermeasure. The safety benefit derived by implementation of an improvement is quantified in terms of the crashes it eliminates (or prevents). This benefit can be estimated using the following equation:

\[
\Delta N = -N_{w/o} \cdot CRF
\]  

(2)

where:

\( \Delta N \) = reduction in crashes due to implementation of a safety improvement (i.e., countermeasure) (= \( N_w - N_{w/o} \)).

A reduction in crashes is mathematically represented as a negative quantity in Equation 2.

When using Equation 2 to compute safety benefits, the expected number of crashes without the improvement \( N_{w/o} \) is typically estimated as the number of reported crashes \( X \) at the subject location. However, it is generally recognized that \( X \) is not a reliable estimate of the long-term average crash frequency at the location (21). In fact, if the location was identified because it is a “high-crash location,” then \( X \) would almost certainly overestimate the expected crash
frequency at the location and the reduction $\Delta N$ (obtained by using $\chi$ in Equation 2) would also be overestimated. Techniques for obtaining unbiased estimates of $N_{w/o}$ and $\Delta N$ are described elsewhere (21).

For improvements that last multiple years, Equation 2 would be applied for each year of the improvement’s design life. The estimate $N_{w/o}$ would be increased each year in direct proportion to the annual increase in AADT. The crash reduction computed for each year would then be summed to yield the total reduction in crashes.

**Safety Effect of Multiple Countermeasures.** Multiple countermeasures are often implemented at the same location. In a recent survey of DOTs, Shen et al. (18) found that very few CRFs have been quantified for combinations of countermeasures. As a substitute, an equation is typically used by the DOTs to predict the combined effect of the individual countermeasures. The form of this equation is:

$$CRF_c = 1 - (1 - CRF_1) \times (1 - CRF_2) \times (1 - CRF_3) \times \ldots \times (1 - CRF_n)$$  \hspace{1cm} (3)

where:

$CRF_c =$ combined CRF for all $n$ countermeasures.

The formulation of Equation 3 implies that a change in any one factor has an effect on the magnitude of all other applicable adjustment factors. This formulation indirectly accounts for the interaction among adjustment factors by moderating the impact of multiple reduction factors. However, to date, there has been no research reported that verifies the accuracy of Equation 3 and the independence of CRFs/AMFs.

To compute the safety benefit $\Delta N$ associated with multiple countermeasures, Equation 3 would first be used to estimate $CRF_c$. Then, this value would then be used in Equation 2 to compute the reduction in crashes attributed to the countermeasures.

**Accident Modification Factors**

In recent years, the concept of CRF has been extended to the more general concept of AMF. This extension reflects the recognition that a change in geometry, traffic control device or signalization could result in either an increase or a decrease in crashes. The term “reduction,” used with CRF, is limiting because it does not recognize the possibility that crashes can increase following a change in roadway design or operation. As discussed by Hauer (22), "Because not all measures may be expected to reduce accidents, the word 'modification' is preferred to the word 'reduction.'" The extension to AMF also facilitates a broader application of the CRF concept in the context of its use with safety prediction models. In this context, AMFs are used with a safety
prediction model to: (1) estimate the expected crash frequency for a specific location, or (2) estimate the effect of a change in conditions on safety.

The intrinsic relationship between the AMF and CRF is defined as (22):

\[
AMF = 1 - CRF
\]
\[
AMF = 1 - \left( 1 - \frac{N_w}{N_{w/o}} \right)
\]
\[
AMF = \frac{N_w}{N_{w/o}}
\]  

When combinations of AMFs are used, Equations 3 and 4 are typically combined to yield the following equation for computing the effect of multiple changes in geometry, traffic control device or signalization:

\[
AMF_c = AMF_1 \times AMF_2 \times AMF_3 \times ... \times AMF_n
\]  

where:

- \( AMF_c \) = combined AMF for all \( n \) changes.

### Expected Crash Frequency for A Specific Location

As noted in Bonneson and Lord (15), an accurate estimate of the expected number of crashes without the improvement \( N_{w/o} \) is needed to develop unbiased CRFs and to accurately estimate the reduction in crashes due to the implementation of a safety improvement \( \Delta N \). This need is extended to the development of AMFs and the estimation of a change in crashes (increase or reduction) due to a change in conditions. However, the variables \( N_w \) and \( N_{w/o} \) are hereafter redefined slightly, relative to their first use in Equation 1. Specifically, the term “change” is hereafter substituted for the word “improvement.” This modification is intended to reflect the broader range of application with AMFs than with CRFs.

Two methods are described in this section for estimating \( N_{w/o} \). The first method presented is easier to apply because it does not require crash data for the subject location. The second method presented does require crash data for the location but yields a more accurate estimate of \( N_{w/o} \).

**Expected Crash Frequency without Knowledge of Crash History.** Harwood et al. (23) recommend the combined use of AMFs and a “base” safety prediction model to estimate \( N_{w/o} \). The base model predicts the crash experience for a location of typical geometric design,
traffic control device usage, and roadside design components. Many atypical discreet factors (e.g., driveways, passing lanes, etc.) would not be represented in the base model. Rather, their safety effect would be accounted for by using the appropriate AMF (e.g., AMF_{driveway}, AMF_{passing lane}) with the base model. Similarly, design elements that have a continuous relationship are represented in the base model at typical values (e.g., no grade, 12-ft lane width). Conditions that are atypical at a particular location are incorporated using the appropriate AMF (e.g., AMF_{grade}, AMF_{lane width}). In this manner, AMFs are used to adjust the base model prediction to reflect conditions at the subject location. The form of this relationship is:

\[ N_p = N_{base} \ AMF_{c,p} \]  

where:

- \( N_p \) = expected number of crashes at subject location, crashes/yr;
- \( N_{base} \) = expected number of crashes for base (i.e., average) conditions, crashes/yr; and
- \( AMF_{c,p} \) = combination of AMFs that describe atypical conditions at the subject location.

Base safety prediction models have been developed by Harwood et al. (23) and others (20, 24). These models can be used for various highway segments and intersection facilities. Most segment models are calibrated for a specific functional class. Most intersection models are calibrated for a specific type of intersection control (e.g., signalized, two-way stop control, etc.) and number of approach legs. The model structure used most often for highway segments is:

\[ N_{base} = a \ AADT^b \ L^{c + d \times \text{other factors}} \]  

where:

- \( AADT \) = annual average daily traffic volume, veh/d;
- \( L \) = roadway length, mi or km; and
- \( a, b, c, d \) = calibration coefficients.

A similar model structure is used for intersections.

When Equations 6 and 7 are used to develop a CRF or AMF or to estimate the effect of a change in safety \( \Delta N \), the variable values used in them should reflect existing conditions at the subject location. In this manner, the value obtained from Equation 6 would represent \( N_{w/o} \) (i.e., \( N_{w/o} = N_p \)). In fact, Equations 6 and 7 are sufficiently general that they can be used to estimate the expected crash frequency for any combination of conditions (existing or proposed).

The base safety prediction model shown in Equation 7 is illustrative of typical base models (20, 23, 24) for roadway segments. The volume and length variables are common to most predictive models. The calibration coefficients are used to scale the model for specific roadway classifications, facility types, and conditions. The “other factors” term represents any additional geometric variables that improve model accuracy.
**Expected Crash Frequency with Knowledge of Crash History.** If the crash history of the subject location is available, the empirical Bayes (EB) method can be used to estimate the expected number of crashes at the subject location \((20, 24)\). This estimate would be more accurate than that obtained from Equation 6 due to the inclusion of the subject location’s crash history in the calculation. It is based on a weighted average of the value from Equation 6 and the reported crash count \(X\) for the subject location. This estimate can be computed using the following equation:

\[
N_{pw} = N_p w + \frac{X}{Y} (1 - w)
\]  

with,

\[
w = \left( 1 + \frac{KN_p Y}{L} \right)^{-1}
\]  

where:

- \(N_{pw}\) = expected number of crashes at subject location given that \(X\) were reported, crashes/yr;
- \(N_p\) = expected number of crashes at subject location (from Equation 6), crashes/yr;
- \(X\) = number of crashes reported at the subject location, crashes;
- \(Y\) = number of years during which \(X\) crashes were reported, yr;
- \(w\) = weight given to \(N_p\);
- \(L\) = roadway length, mi or km; and,
- \(K\) = inverse dispersion parameter.

The inverse dispersion parameter used in Equation 9 is an empirical constant that represents the amount of variability in the crash data used for model calibration. This value is obtained from the regression analysis used to calibrate the base safety prediction model. A unique value exists for each model and database, although recent work shows otherwise \((24, 25)\).

When Equations 6 through 9 are used to develop a CRF or AMF or to estimate the effect of a change in safety \(\Delta N\), the variable values used in Equations 6 and 7 should reflect existing conditions at the subject location. In this manner, the value obtained from Equation 6 would represent \(N_{w/o}\) (i.e., \(N_{w/o} = N_{p|x}\)).

**Application of Accident Modification Factors for Estimating the Safety Effects of Proposed Projects**

This section describes the basic method of applying AMFs in the design process. Initially, it describes the evaluation of a single design change. Then, it describes a technique for evaluating several design changes when they are to be combined into one project. The application method is more formally described and illustrated in the last section of this paper.
Safety Effect of One Design Change without Knowledge of Crash History. A variation of Equation 2 can also be used to estimate the effect of a change on safety. Initially, the expected number of crashes for the base condition is computed using Equation 7. Then, the set of AMFs needed to tailor the base crash frequency to that of the existing location are combined using Equation 5. Next, the expected number of crashes at the subject location $N_p$ is obtained from Equation 6. It serves as an estimate of $N_{w/o}$ (i.e., $N_{w/o} = N_p$). Then, an AMF representing the specified change in condition is identified as is its counterpart in the set of AMFs previously used to compute $N_p$. Finally, the following equation is used to estimate the expected change in crashes due to the change in condition:

$$\Delta N = N_{w/o} \left( \frac{AMF_{w/o}}{AMF_{w}} - 1 \right)$$

where:
- $\Delta N$ = change in crashes due to a change in condition ($= N_w - N_{w/o}$), crashes/yr;
- $N_{w/o}$ = expected number of crashes without the change ($= N_p$), crashes/yr;
- $AMF_{w/o}$ = AMF of design component to be changed but reflecting existing conditions; and
- $AMF_{w}$ = AMF of design component to be changed, reflecting the changes.

A positive value of $\Delta N$ denotes an increase in crash frequency.

For changes that last multiple years, Equation 6 would be reapplied for each year of the change’s design life. Specifically, the AADT for each year of the design life would be estimated and used in Equation 6 to compute $N_{w/o}$ for that year. Then, the change in crashes for each year would be computed using Equation 10 with the yearly estimates of $N_{w/o}$. The AMF variables (i.e., $AMF_{c,p}$ and $AMF$) are constant for each year. The change in crashes for each year is summed for all years to yield the total change in crash frequency.

Safety Effect of One Design Change with Knowledge of Crash History. This section describes a method for estimating the effect of a change in conditions on safety when the crash history is known. This method improves the accuracy of the estimate obtained from Equation 10 by combining the reported crash count at a specific location with the expected crash frequency obtained from Equation 6. The combined quantity represents the expected crash frequency without the change, given that $X$ crashes were reported $N_{w/o|x}$.

Initially, the expected number of crashes for the base condition is computed using Equation 7. Then, the set of AMFs needed to tailor the base crash frequency to that of the existing location are combined using Equation 5. Next, the expected number of crashes at the subject location $N_p$ is obtained from Equation 6. Then, $N_p$ is used in Equation 8 with the reported crash count $X$ to estimate $N_{p|x}$. It serves as an estimate of $N_{w/o|x}$ (i.e., $N_{w/o|x} = N_{p|x}$). Then, an AMF representing the specified change in condition is identified as is its counterpart in the set of
AMFs previously used to compute $N_p$. Finally, $N_{w/o|x}$ is substituted into the following equation and used to compute the impact of the change in terms of the crashes it eliminates (or causes):

$$\Delta N = N_{w/o|x} \left( \frac{AMF_w}{AMF_{w/o}} - 1 \right)$$  \hspace{1cm} (11)

For changes that last multiple years, Equation 6 would be reapplied for each year of the change’s design life. Specifically, the AADT for each year of the design life would be estimated and used in Equation 6 to compute $N_{w/o}$ for that year. Next, the value of $N_{w/o, i}$ obtained for year $i$ is used with the following equation to compute the corresponding $N_{w/o|x, i}$ for the same year:

$$N_{w/o|x, i} = N_{p|x} \frac{N_{w/o|x, i}}{N_{w/o, 1}}$$  \hspace{1cm} (12)

where:

$N_{w/o, i}$ = expected number of crashes without the change based on the conditions (e.g., traffic volumes) present in year $i$ ($i = 1, 2, ..., n$), crashes/yr.

In Equation 12, $N_{p|x}$ and $N_{w/o, 1}$ are constant for each year. The value $N_{w/o, 1}$ is obtained from Equation 6 using conditions present in the first year (i.e., $N_{w/o, 1} = N_p$). It is substituted for $N_p$ in Equation 8 along with the reported crash count $X$ to estimate $N_{p|x}$.

Once the yearly values of $N_{w/o|x, i}$ are computed, they are used with Equation 11 to estimate the change in crashes that occur for each year $i$. The AMF variables (i.e., $AMF_{c,p}$ and $AMF$) are constant for each year. The change in crashes for each year is summed for all years to yield the total change in crash frequency.

**Safety Effect of Multiple Design Changes without Knowledge of Crash History.**

Multiple changes are often considered for the same location. If an AMF is not available for the combination being considered, Equation 5 can be used to estimate the combined effect of the individual changes. The following steps are used to compute the change in safety that is associated with multiple design changes.

Initially, the expected number of crashes for the base condition is computed using Equation 7. Then, the set of AMFs needed to tailor the base crash frequency to that of the existing location are combined using Equation 5. Next, the expected number of crashes at the subject location $N_p$ is obtained from Equation 6. It serves as an estimate of $N_{w/o}$ (i.e., $N_{w/o} = N_p$). Then, the AMFs representing the specified change in conditions are identified as are their counterparts in the set of AMFs previously used to compute $N_p$. There should be a one-to-one
match between the two sets of AMFs used, in terms of the design components that each AMF addresses.

The AMFs corresponding to the specified design components to be changed but reflecting the existing conditions are defined as $AMF_{c, w/o}$. Those AMFs corresponding to the components to be changed and reflecting these changes are defined as $AMF_{c, w}$. Equation 10 is used with these estimates to obtain the change in crashes.

**Safety Effect of Multiple Design Changes with Knowledge of Crash History.** The effect of multiple changes in conditions can also be evaluated when crash history is available. In this instance, the same procedure as that described for “one change with knowledge of crash history” is used. However, the procedure described in the previous section for estimating $AMF_{c, w/o}$ and $AMF_{c, w}$ is used.

**DESIGN APPLICATIONS OF AMFs WITHIN THE HIGHWAY DESIGN PROCESS**

Three potential design applications of AMFs are described in this section. Two of the applications relate to the direct evaluation of safety as part of the preliminary design stage and the design exception process. The third application relates to the evaluation of design consistency during the preliminary design stage. There are obviously other relevant applications where AMFs could be used, such as access management or context sensitive design, but are not addressed in this work and we beyond the original scope of the project.

**Safety Evaluation - Preliminary Design Stage**

The major design features of the roadway are usually defined during the preliminary design stage. During this stage, alternative locations and features are considered and the most promising ones are evaluated in greater detail. This stage of the design process was illustrated in Figure 1 and has been described previously by Bonneson et al. (26).

Some evaluation tools are used in the preliminary design stage to assess the operational performance, environmental impact, right-of-way requirement, and construction cost of various design alternatives. Safety evaluation tools are being developed to facilitate the assessment of the safety. The objective of the assessment is to ensure that the design offers a reasonable balance between cost and effectiveness. Collectively, these tools can be used together to quantify the cost and effectiveness of each alternative.

The following tools are being developed nationally to facilitate the quantitative evaluation of safety benefit during the design process:
AMFs are used in each of these tools to facilitate the evaluation of design alternatives.

Safety Evaluation - Design Exception Process

In some circumstances, it may not be practical or reasonable to require a design to satisfy each and every design criterion. In some situations, it may in fact be extremely expensive to adhere to a specific criterion. In other instances, adherence may impose a significant hardship on adjacent land owners or local residents. The process of evaluating a request for deviation from agency-adopted design criteria and making a decision to grant or deny the request is known as the “design exception process.” The objective of this evaluation is to ensure that the safety and operational efficiency of the facility are kept in balance with other design-related impacts (e.g., aesthetics, environment) and are reflective of the funds available for construction. The design exception process is usually handled on a case-by-case basis. This process varies greatly from state to state, where each DOT has their own organizational structure, review, documentation, and approval processes (28).

Safety evaluation tools can be used to assist in the evaluation of design exceptions. These tools could be used to quantify the change in crash frequency that would likely occur if the design exception was, and was not, granted. From this analysis, one of the following conclusions might be reached in support of the request:

- There is likely to be fewer total crashes and no increase in the portion of severe (i.e., injury or fatal) crashes.
- There is likely to be no change in total crashes and no increase in the portion of severe crashes.
- There is likely to be an increase in total crashes but the increase will be offset by a reduction in the number of fatal and injury crashes.

Information used to reach one of the aforementioned conclusions could be obtained using Equation 10 or 11 to compute the change in crashes for the case where the design exception request is granted and again for the case where it is not granted. Of the two equations, Equation 11 is likely to yield the more accurate estimate of $\Delta N$ because it includes information about a large sample of similar locations as well as the reported crash count $X$. As noted previously, the use of AMFs with only the reported crash count may overstate the change in crashes because of regression-to-the-mean and site selection biases.
Design Consistency Evaluation - Preliminary Stage

Design consistency is the conformance of a highway’s geometric and operational features with driver expectancy (29). Geometric features that are unexpected or atypical (relative to previously encountered features) may increase the risk of driver error, which may decrease the safety of the highway segment, intersection, or interchange. As noted by Alexander and Lunenfeld (30), driver expectancy is an important component of the driving task and can significantly affect the risk of a crash. Thus, by improving design consistency, it is anticipated that a facility will operate with fewer failures (e.g., driver errors) and related crashes.

Research on the topic of design consistency has taken the form of design consistency checklists, speed change evaluations, and driver workload considerations. Less attention has been paid to the quantification of the safety benefits of design consistency. However, recent research projects have developed tools to measure design consistency (29) and its relationship to safety (31).

Wooldridge et al. (29) recommend the use of AMFs to identify when a change in a specific design component is sufficiently significant as to be deemed “inconsistent with driver expectancy.” In this application, they recommend using the change in AMF associated with successive road segments as a means of identifying inconsistencies. They specified threshold values of AMF change for this purpose. It should be noted that this application does not require the use of a base safety prediction model or the reported crash count.

It is important to point out that the applications described above will be governed by the accuracy and the un-biased estimates of these factors. Recent research has identified several issues that are likely to result in biased estimates of CRFs/AMFs if proper statistical techniques are not employed (13, 14, 15). In fact, there is compelling evidence that many of the CRFs developed for the HES program have some bias in them (32). This bias has been attributed to many problems associated with before-after or cross-sectional studies not well understood in previous years. New statistical techniques have been developed or are currently in development to mitigate this bias. The next section describes the procedure for each application. A step-by-step example is presented to help describe each procedure.

APPLICATION OF EVALUATION PROCEDURE

This section describes the procedure for applying AMFs within the highway design process. These applications include:

- safety evaluation of design alternatives,
- safety evaluation of design exceptions, and
- design consistency evaluation.
The evaluation of design safety consists of the prediction of crash frequency associated with one or more alternative design components (e.g., horizontal curve) and the sizes of the various elements of which they are comprised (e.g., radius, superelevation rate). This evaluation would likely occur during the preliminary design stage of the design process. Information from this evaluation would be used in the selection of the preferred design component.

The evaluation of design exceptions consists of predicting the effect of a design exception on crash frequency. In this application, one or more AMFs would be used to quantify the safety implications of a proposed deviation from a design control value.

The evaluation of design consistency consists of quantitatively assessing the degree of conformance between driver expectancy and a highway’s geometric features, operational features, or both. Significant changes in design character (e.g., cross section) among adjacent road segments that are unexpected can lead to increased driver workload and a reduction in the level of safety. Information from this evaluation would be used to either maintain consistency in roadway design or facilitate the introduction of changes in design character at a rate that does not compromise safety.

**Safety Evaluation of Design Alternatives**

For the evaluation of design safety, AMFs are used to compare the safety effects of different highway design components. For instance, a designer may be interested in choosing between two alternative horizontal curve radii. The goal is to quantify the crash frequency for the geometric design alternatives and use this information as part of comprehensive analysis of the benefits and costs of each design alternative. A procedure for achieving this goal is described in the next section. Thereafter, it is illustrated in an example application.

**Procedure**

The procedure for estimating the safety effects of changes in geometric design components consists of two elements: base safety prediction models and AMFs. In this procedure, Equation 7 is first used to estimate the expected number of crashes for base conditions \( N_{\text{base}} \). Then, AMFs are used in Equation 6 to adjust the value obtained from the base model such that the result is an estimate of the expected crash frequency associated with the existing or initial design \( N_{\text{w/o}} \). Next, a design change is specified and the corresponding AMF is identified. Finally, the change in safety \( \Delta N \) is quantified using Equation 10.

If the project is associated with an existing alignment, the reported crash count \( X \) can be used to improve the accuracy of the estimated expected crash frequency associated with the existing or initial design. In this variation of the estimation procedure, Equation 8 is used to estimate the expected crash frequency given that \( X \) crashes were reported \( N_{\text{p|x}} \). This value is then
equated to $N_{\text{w/o}}$ and used with Equation 11 to estimate the change in safety due to the change in conditions $\Delta N$.

**Example Application 1**

In this example application of the design safety evaluation, a 3-mile two-lane rural highway segment linking two major intersections is being reconstructed. This segment contains one tangent section without any vertical curves. Existing lane widths are 11 ft with no shoulder. Current traffic volume is estimated at 5000 veh/d. All other conditions are the same for both the existing condition and the design alternative.

**Step 1: Estimate Expected Number of Crashes for Base Conditions.** The safety prediction model described in the draft prototype chapter (DPC) for estimating the safety performance of rural two-lane highways can be obtained from Equation 7 by substituting the following values for the calibration coefficients: $a = 0.0002244$, $b = 1.0$, $c = 0.0$, and $d = 0.0$. (Note: the methodology proposed in the DPC has still not yet been officially adopted by the HSM Task Force.) Using this model, the expected number of crashes for the base condition is estimated as:

$$N_{\text{base}} = 0.0002244 \times \text{AADT} \times L$$

$$= 0.0002244 \times 5000 \times 3$$

$$= 3.37 \text{ crashes/yr}$$

This equation predicts crash frequency for a road segment having a specified set of typical design element dimensions. The dimensions that underlie Equation 13 include 12-ft lanes and 6-ft shoulder widths.

**Step 2: Adjust Base Conditions to Reflect Existing or Initial Design.** Using AMFs available from, the value from Equation 13 is adjusted to reflect existing conditions (i.e., 11-ft lanes, and no shoulder). These AMFs are $AMF_{\text{lane_width}} = 1.02$ and $AMF_{\text{shoulder_width}} = 1.18$. The result of this computation is:

$$N_{\text{w/o}} = (AMF_{\text{lane_width}} \times AMF_{\text{shoulder_width}}) \times 3.37$$

$$= (1.02 \times 1.18) \times 3.37$$

$$= 4.06 \text{ crashes/yr}$$

**Step 3: Specify a Design Change and Identify the Appropriate AMFs.** The designer has identified a design alternative as having 12-ft lanes with 8-ft paved shoulders. From the DPC, AMFs are identified for the changes in lane and shoulder width as $AMF_{\text{lane_width}} = 1.00$ and $AMF_{\text{shoulder_width}} = 0.95$. 
Step 4: Compute Safety Change. The change in safety as a result of the alternative lane and shoulder widths can be estimated as:

$$\Delta N = 4.06 \left( \frac{1.00 \times 0.95}{1.02 \times 1.18} - 1 \right)$$

$$= -0.86\ \text{crashes/yr}$$ (15)

The alternative is estimated to reduce crash frequency on the segment by 0.86 crashes/yr. From a safety perspective, this alternative is attractive. It should be pointed out that this estimate represents only one piece of information about the alternative; the decision to accept or reject this alternative should be made in the larger context of its overall impact on operation, safety, right-of-way, and construction cost.

Safety Evaluation of Design Exceptions

Design exceptions often represent one of two scenarios. The first scenario occurs when an existing highway is considered for reconstruction and one or more of its design components do not meet current design criteria. An exception might be needed if there are significant adverse impacts associated with bringing the roadway into compliance with current criteria. For example, a highway was in compliance with the criteria “of the day” when it was originally designed with 11-ft lanes and 2-ft shoulders. However, it is now being considered for reconstruction and the current criterion requires provision of 12-ft lanes and 8-ft shoulders. If the right-of-way impacts associated with widening the roadway are significant, a design exception may be requested to allow continued use of the existing cross section, which should include the safety effect of this exception.

The second scenario occurs when a roadway component that is compliant with current criteria is being reconstructed and a proposed new value for its dimension does not meet the minimum threshold for a controlling criterion. In this scenario, the change is in a direction of “compliant” with the current controlling criterion to “not compliant.” For example, a multilane highway has four 12-ft lanes and 8-ft shoulders that are compliant with current criteria. It is now being considered for reconstruction that would include the provision of a center turn lane; however, right-of-way constraints preclude any widening of the roadway. A design exception may be requested to allow the use of five 10-ft lanes and 7-ft shoulders.

AMFs are less likely to be available for the second scenario because agencies rarely implement changes in this manner (in which case they are difficult to study). Such AMFs are referred to herein as “non-compliant AMFs.” More generally, AMFs are developed using crash data for design features that are brought into compliance with a design criterion. These AMFs are referred to herein as “compliant AMFs.” In some instances, it is possible to mathematically estimate a non-compliant AMF using a compliant AMF (e.g., by taking its reciprocal).
However, the use of converted AMFs to evaluate a design exception (in the context of the second scenario) would represent a significant extrapolation and would be of suspect accuracy.

**Procedure**

The procedure for estimating the safety effect of a design exception is similar to that used to evaluate design alternatives; however, the use of the existing crash counts is recommended because of the improved accuracy that they provide. In this procedure, Equation 7 is first used to estimate the expected number of crashes for base conditions $N_{\text{base}}$. Then, AMFs are used in Equation 6 to adjust the value obtained from the base model such that the result is an estimate of the expected crash frequency associated with the existing design $N_{w/o}$. Next, the existing crash count $X$ is used with $N_{w/o}$ in Equation 8 to estimate the expected number of crashes at the subject location, given that $X$ were reported $N_{p|x}$. It serves as an estimate of $N_{w/o|x}$ (i.e., $N_{w/o|x} = N_{p|x}$). Then, a design change is specified and the corresponding AMF is identified. Finally, the change in safety $\Delta N$ is quantified using Equation 14.

**Example Application 2**

In this example application of the design safety evaluation, a 3-mile two-lane rural highway segment linking two major intersections is being reconstructed. Existing lane widths are 11 ft with no shoulders. The traffic volume is estimated at 5,000 veh/d. The controlling criteria for this project require 12-ft lanes and 8-ft shoulders. However, existing land development is intensive, and acquisition of the needed additional right-of-way would be significant. Existing crash history indicates the occurrence of nine crashes in the previous three years along the segment.

**Step 1: Estimate Expected Number of Crashes for Base Conditions.** The safety prediction model included in the DPC (8) can be obtained from Equation 7 by substituting the following values for the calibration coefficients: $a = 0.0002244$, $b = 1.0$, $c = 0.0$, and $d = 0.0$. Using this model, this gives the same results as for Equation 13:

$$N_{\text{base}} = 0.0002244 \times ADT \times L$$
$$= 0.0002244 \times 5000 \times 3$$
$$= 3.37 \text{ crashes/yr} \quad (16)$$

This equation predicts crash frequency for a road segment having a specified set of typical design element dimensions. The dimensions that underlie Equation 16 include 12-ft lanes and 6-ft shoulder widths (9).

**Step 2: Adjust Base Conditions to Reflect Existing Design.** Using AMFs available in the DPC (8), the value from Equation 16 is adjusted to reflect existing conditions (i.e., 11-ft lanes,
and no shoulder). These AMFs are $AMF_{lane\_width} = 1.02$ and $AMF_{shoulder\_width} = 1.18$. The result of this computation is:

$$N_{w/o} = (AMF_{lane\_width} \times AMF_{shoulder\_width}) \times 3.37$$
$$= (1.02 \times 1.18) \times 3.37$$
$$= 4.06 \text{ crashes/yr} \tag{17}$$

**Step 3: Estimate the Expected Number of Crashes Given that $X$ were Reported.**

Equation 8 is used to refine the estimate of expected crash frequency based on the estimate from Equation 17 and the reported crash count. First, the weight $w$ is computed from Equation 9 as:

$$w = \left(1 + \frac{K N_p Y}{L}\right)^{-1}$$
$$= \left(1 + \frac{0.24 \times 4.06 \times 3}{3.0}\right)^{-1}$$
$$= 0.51 \tag{18}$$

The value of $K$ (i.e., 0.24) used in this equation is provided in Exhibit 15 of the DPC in (8). The weight $w$ is then used in Equation 8 to estimate $N_{w/o|X}$ as

$$N_{w/o|X} = N_{w/o} w + \frac{X}{Y} (1 - w)$$
$$= 4.06 (0.51) + \frac{9}{3} (1 - 0.51)$$
$$= 3.54 \text{ crashes/yr} \tag{19}$$

The fact that 3.54 is less than 4.06 is an indication that the subject highway segment is safer than similar segments with similar volume and geometry. It should also be noted that nine crashes in three years represents an average of 3.0 crashes/yr yet Equation 19 indicates that this average underestimates the true, long-run average of 3.54 crashes/yr.

**Step 4: Specify the Design Change and Identify the Appropriate AMF.** The design change to be evaluated is that needed to bring the segment into compliance with the controlling criteria. In this example, the design change is the use of 12-ft lanes and 8-ft shoulders, as required by the existing design criteria. From (8), AMFs are identified for the changes in lane and shoulder width as $AMF_{lane\_width} = 1.00$ and $AMF_{shoulder\_width} = 0.95$. 
Step 5: Compute Safety Change. The change in safety as a result of compliance with the controlling shoulder width criterion is:

\[
\Delta N = 3.54 \left( \frac{1.00 \times 0.95}{1.02 \times 1.18} - 1 \right) = -0.75 \text{ crashes/yr}
\]

From this computation, it appears that compliance with the shoulder width criterion is estimated to reduce crash frequency on the segment by 0.75 crashes/yr (i.e., three crashes in four years). Alternatively, granting the request may result in there being three more crashes in a four-year period than if it were denied. The analysis above was repeated using only severe crash frequency. It was found that maintaining the existing (narrow) lanes and shoulders may result in there being one more severe crash in a four-year period.

From a safety perspective, requiring compliance with current criteria is attractive. However, this estimate represents only one piece of information about the effect of a design exception; the decision to accept or reject the request should be made in the larger context of its overall impact on operations, safety, right-of-way, and construction cost. For example, if the extra lane and shoulder width require a reduction in clear zone width, then crashes may actually increase if the request for exception is denied and the clear zone is reduced. The procedure described herein can be used to evaluate this combination of conditions, if needed.

It should be noted that Steps 4 and 5 could be repeated for other lane or shoulder widths and the incremental effect of this width evaluated in more detail. It is possible that the consideration of all impacts may lead to the conclusion that an exception that allows for a 6-ft shoulder width may offer the best combination of conditions.

Design Consistency Evaluation

As described previously, geometric features that violate driver expectancy may increase the risk of driver error and decrease the safety of the roadway. Recent research on this topic has focused on quantifying the safety effects of design inconsistencies for various geometric elements. In fact, Wooldridge et al. (29) proposed the use of changes in AMF, speed, and lane position to identify design inconsistencies for successive rural two-lane highway segments. The following geometric design elements were included in their analysis: lane width, shoulder width, lane drop, driveway addition, and length of passing lanes.
Procedure

For reductions in lane width and shoulder width, Wooldridge et al. (23) suggest the use of the following equation to estimate the impact on design consistency:

\[
AMF\% = 100 \left( \frac{AMF_{Segment 2}}{AMF_{Segment 1}} - 1 \right)
\]  

(21)

In this equation, Segments 1 and 2 are numbered in the direction of travel.

Wooldridge et al. suggest that a design inconsistency exists if the \(AMF\%\) exceeds specified critical values. The first two rows in Table 1 summarize the critical values proposed by Wooldridge et al. (29) for lane width and shoulder width. These values correspond to a two-level warning system. Level 1 denotes a condition for which mitigation is strongly encouraged. Level 2 denotes a condition deserving of an advisory warning and a suggested need for improvement. It should be noted that inconsistencies are stated to exist only when the lane width or shoulder width is reduced.

<table>
<thead>
<tr>
<th>Design Component</th>
<th>Applicable AMF Variable</th>
<th>Critical Values by Warning Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction in lane width</td>
<td>(AMF%)</td>
<td>Level 2: 5.0 %</td>
</tr>
<tr>
<td>Reduction in shoulder width</td>
<td>(AMF%)</td>
<td>Level 2: 5.0 %</td>
</tr>
<tr>
<td>Driveway density</td>
<td>(\Delta AMF)</td>
<td>0.05</td>
</tr>
</tbody>
</table>

For changes in driveway density, Wooldridge et al. (29) suggest the use of the following equation to estimate the impact on design consistency:

\[
\Delta AMF = AMF_{Segment 2} - AMF_{Segment 1}
\]  

(22)

The critical values associated with this equation are listed in the last row of Table 2. Inconsistencies are noted to exist only when driveway density increases between adjacent highway segments.

It should be noted that this procedure has not been validated through practical application. As such, it should be considered experimental and any results from its use carefully examined. The main point of the discussion in this section is that some researchers believe
AMFs may be useful in evaluating design consistency. However, additional work is needed to: (1) refine the evaluation procedure so that it can be used with a wider range of design components, and (2) confirm the validity of the critical AMF warning levels.

Example Application 3

In this example application of the design consistency evaluation procedure, a 3-mile two-lane rural highway segment linking two major intersections is being reconstructed. The segment AADT is 5000 veh/d. For the first 1.5 miles, the segment has lane widths of 12 ft and shoulder widths of 8 ft. For the last 1.5 miles, the shoulder width is reduced to 4 ft. The traffic volume is estimated at 5000 veh/d.

The evaluation of design consistency for the subject highway is based on a comparison of the two AMFs for shoulder width. The AMF for the shoulder width on the first segment $AMF_{\text{segment 1}}$ is 0.95 ($\frac{8}{8}$). The AMF for the shoulder width on the second segment $AMF_{\text{segment 2}}$ is 1.05. Equation 21 is used to estimate the effect of this change on design consistency as:

$$AMF\% = 100 \left( \frac{1.05}{0.95} - 1 \right)$$

$$= 11\%$$

(23)

The reduction in shoulder width results in an 11-percent change in AMF. This value exceeds the critical value of 10 percent identified in Table 2 indicating a Level 1 violation of design consistency. Guidance by Wooldridge et al. (29) states that strong consideration should be given to increasing the shoulder width to 8 ft throughout the segment.

SUMMARY AND CONCLUSIONS

This paper has described the role and application of AMFs in the highway geometric design process. It first depicted the role AMFs have played in safety evaluation and analysis. Then, the paper covered three potential applications of AMFs within the design process. More specifically, it provided guidelines for applying these factors within the preliminary design stage, for assessing design consistency and for evaluating design exceptions. For each design application, a proposed procedure was described in details. An example was provided for each design application to better illustrate the description of the procedure. The description presented in this paper has shown that AMFs can play an important role for different applications commonly used within the highway design process. Although AMFs could be used in other types of application, it is the hope that the procedures described herein will be very beneficial for practitioners, highway designers, and transportation planners who are involved in the development and design of highways.
REFERENCES


