Safety Planning Study of Urban Freeways

Proposed Methodology and Review of Case History

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Safety-conscious planning is a relatively new concept. It was developed in response to safety-related provisions of the Transportation Equity Act for the 21st Century (TEA-21) of 1998, which required explicit consideration of safety in the transportation planning process. The problem of using accident rates in transportation planning is revisited, and a case history of applying safety-conscious planning methods by the Colorado Department of Transportation is reviewed. A two-phase process that has been used to evaluate the safety impacts of multiple design alternatives is introduced. The evaluation process is based on the available safety performance functions calibrated specifically for urban freeways in concert with diagnostic investigations, pattern recognition analysis, and detailed accident diagramming. The critical importance of accident diagramming is discussed in reference to examining safety history at complex interchange locations.

A number of major freeway corridor planning studies are currently under way in the Denver, Colorado, metropolitan area. The primary effort of these corridor studies is focused on providing additional mobility while considering safety to meet the growing travel demand along the Rocky Mountain Front Range. How to deliver this increased mobility with multimodal transport facilities is a matter of some debate, yet the underlying methodology is reasonably well understood and accepted currently. How to provide safety, however, is not as well understood.

What is the best way to measure safety? How much safety for how much money can people expect? Are roads designed to standards as safe as they should be or as safe as they could be? These fundamental questions have not been answered with the kind of accuracy customary in the engineering discipline.

At the same time that definitive answers to basic questions on highway safety are sought, the Transportation Equity Act for the 21st Century (TEA-21) currently requires the explicit consideration of safety in the transportation planning process. Although this government mandate is well intentioned, little is known about how best to fulfill it. Hauer observed:

> Today one can devise a long-term transportation plan for a region, one can get approval for a road network in a new subdivision, one can implement a traffic signal coordination and timing plan for a metropolis, one can design a new highway and, in all this, never consider the future crash frequency and severity differences between options and alternatives. (*1*)

The National Environmental Policy Act (NEPA) requires that for each transportation alternative under consideration, environmental impacts be identified and mitigation options described clearly within the framework of an environmental assessment or an environmental impact statement (EIS). In contrast to this environmental approach, the safety impacts of design alternatives are not addressed explicitly but rather by the proxy of meeting standards. Even when design standards are met, however, different alternatives provide different levels of safety.

Road safety is always a matter of degree, but are efforts to provide an adequate level of safety on a transportation facility less important than those targeting environmental protection? It seems to make sense that the evaluation of multiple design alternatives should include a rigorous assessment of their safety impacts. Such a safety assessment could be a critical factor in selecting the superior design option and concurrently satisfy the safety obligations of TEA-21. Safety assessments specifically evaluating the safety impacts of design alternatives are now standard practice at the Colorado Department of Transportation (CDOT) when transportation improvements are planned. A practical methodology used at CDOT for the explicit consideration of safety in planning freeway corridor projects is presented and a case history is reviewed.

ACCIDENT RATES AS SAFETY MEASURE

A recent study by Ravanbakht et al. (*2*) compiled an extensive regional crash database in Virginia to assist with regional planning. The authors collected accident data for 130 mi of Interstate highway and 13,000 intersections. Following crash data collection, the freeway and intersection sites were ranked by descending weighted accident rates. Use of accident rates implies a linear relationship between traffic exposure and the number of accidents, which is not always true. Substantial empirical evidence derived from observing the safety performance of various roads by Kononov and Allery (*3*), as well as others, suggests that accident rates decline when annual average daily traffic (AADT) reaches a certain threshold unique to a particular facility. The study by Ravanbakht et al. represents a good starting point; however, the use of accident rates for ranking what can be called sites with promise for safety improvement would always lead to placing those sites with lower AADT at the top of the list.

The following example is intended to illustrate problems inherent in using accident rates as a measure of safety. A section of two-lane, rural mountainous highway in Colorado exhibited the following accident history and accident rates during a study period from 1988 through 1995 over a distance of 5.85 mi. In 1992 the mountain town

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located at the end of the highway section opened gambling casinos and virtually overnight the traffic volume on the highway section quadrupled. The accident rates, measured in accidents per million vehicle miles traveled (acc/mvmt), were computed as follows, and the results are shown in Table 1.

$$\text{accident rate} = \frac{(\#\,\text{accidents})(1{,}000{,}000)}{(365\ \text{days})(\text{AADT})(5.85\ \text{miles})} \tag{1}$$

During the 4-year period before the opening of the casinos, the average accident rate was 2.28 acc/mvmt. The following 4 years after legalization of gambling in this town, the accident rate was reduced by almost 50%. The alignment and typical section of the highway did not change with the introduction of gambling, yet by measuring safety with accident rates it could be surmised that following the opening of the casinos, safety on the same highway improved by 50%. Further, it is of interest to note that following gambling, the proportion of accidents in one direction that involved alcohol (returning home after gambling) increased five times. This finding begs the question: are drinking and driving in concert with gambling good for safety? Probably not, but if accident rates are used as a measuring device, one would have to conclude that they are. In his work *Physics and Philosophy* (*4*), Heisenberg observed:

> Since the measuring device has been constructed by the observer . . . we have to remember that what we observe is not nature in itself but nature exposed to our method of questioning.

The example just presented clearly shows that accident rates change with AADT and suggests that a measuring device other than accident rate be used to measure safety.

Hauer and Persaud (*5*) introduced a more objective measure of safety by using safety performance functions (SPFs). SPFs, in essence, are accident prediction models, which relate traffic exposure, measured in AADT, to safety measured in the number of accidents over a unit of time. Details concerning data set preparation and model fitting for the development of the SPF are described by Hauer (*6*), Lord et al. (*7*), and Kononov and Allery (*3*). The model parameters in the current study were estimated by the maximum likelihood method in the generalized linear modeling (GLM) framework with a data set containing 10 years of accident history. In all cases, accident data in the urban area exhibited extra variation or overdispersion relative to the Poisson model.

TABLE 1 Accident History and Rate Table

Year	No. of Accidents	AADT	Rate	Avg. Rate
Before gambling				
1988	13	2,900	2.11	2.28
1989	11	2,900	1.79	
1990	13	3,050	2.01	
1991	23	3,400	3.19	
After gambling				
1992	30	10,618	1.33	1.24
1993	30	13,200	1.07	
1994	36	14,300	1.19	
1995	40	13,900	1.36	

Development of the SPF lends itself well to the conceptual formulation of the level of service of safety (LOSS). The concept of level of service uses quantitative measures to characterize the observed safety of a roadway segment in reference to the safety performance expected for similar types of roadways. If the level of safety predicted by the SPF represents the normal or expected number of accidents at any specified level of AADT, the degree of deviation from this norm can be stratified to represent specific levels of safety. The delineated LOSS boundary line is located 1.5 standard deviations from the expected line or SPF. In selecting 1.5 standard deviations in a Poisson or negative binomial structure, identification was sought of both those segments of highways with some potential for accident reduction and those segments performing well. Alternatively, stratifying the data set by 2 or more standard deviations would distinguish only extreme or unusual cases. Four levels of LOSS were proposed by Kononov and Allery (*3*):

- LOSS I indicates low potential for accident reduction,
- LOSS II indicates better-than-expected safety performance,
- LOSS III indicates less-than-expected safety performance, and
- LOSS IV indicates high potential for accident reduction.

Although LOSS defines the magnitude of the safety problem, it is important to understand that accident patterns may exist without overrepresentation in total frequency or be readily detectable by SPF methods. The LOSS concept is widely used by CDOT in system-level planning as well as project scoping and is described by Kononov and Allery (*8*).

LOSS reflects how a roadway segment is performing in reference to its expected accident frequency and severity at a specific level of AADT. It only provides a comparison with the expected norm. It does not provide any information related to the nature of the safety problem itself. If a safety problem is present, LOSS will only describe its magnitude. The nature of the problem is determined through diagnostic analysis with direct diagnostics, pattern recognition techniques, and accident diagramming in concert with site visits and plan reviews. In the course of the in-depth, project-level safety study of hundreds of locations, a comprehensive methodology was developed to conduct diagnostic analysis of safety problems for different classes of roads in various environments. Direct diagnostic methods and a pattern recognition algorithm are described by Kononov (*9*) and by Kononov and Janson (*10*).

ACCIDENT DIAGRAMMING

Several NEPA studies examining existing urban freeway corridors are currently under way in the Denver metropolitan area. As part of these studies, the traffic safety impacts associated with the work are considered. The safety provisions of one study will be reviewed as a case history from the standpoint of addressing safety in an EIS context.

The study involves two heavily congested, older, six-lane urban freeways: Interstate 25 and the 6th Avenue freeway, or State Highway 6 (SH-6). When safety improvements are planned for an existing corridor, it is necessary to identify the nature and magnitude of the current safety problem.

The magnitude of the problem is determined by using the LOSS concept, whose use makes it possible to

- Describe quantitatively and qualitatively the degree of safety or lack of safety on a roadway segment,
- Communicate effectively the magnitude of the safety problem to other professionals or elected officials,

- Bring the perception of roadway safety in line with the reality of safety performance reflecting a specific facility, and
- Provide a frame of reference for decision making on non-safety-motivated projects.

The nature of the safety problem, again, was described through diagnostic analysis with direct diagnostics, pattern recognition techniques, and accident diagramming in conjunction with site visits and plan reviews.

To conduct direct diagnostic and pattern recognition analysis in complex areas typical of urban environments, accident diagramming must be used. It will become obvious from the case history presented later that without detailed accident diagramming it is virtually impossible to identify and define problems related to interchange ramps and ramp-connected intersections.

The safety chapter of the EIS encompasses two phases. Phase I prepares a framework for the evaluation of alternatives from a safety standpoint and accomplishes the following:

- Assessment of the magnitude and nature of the safety problem within the project limits;
- Relation of accident causality to roadway geometrics, roadside features, traffic control devices, traffic operations, driver behavior, and vehicle type;
- Suggestion of cost-effective countermeasures to address identified problems; and
- Guidance on how to identify the preferred alternative from a safety standpoint.

Phase II assesses how well each alternative addresses safety problems identified in Phase I. The extent to which these problems are addressed is quantified by the estimated accident reduction for each design alternative, which is based on the nature and magnitude of the existing safety problem and its susceptibility to correction. These estimates are inherently associated with some degree of uncertainty, yet this approach is believed to allow the identification of design alternatives that are more safe than others. The estimated accident reduction for each design alternative is based on the nature and magnitude of the existing safety problem and its susceptibility to correction. Because of space requirements, only selected elements of Phase I and Phase II of the EIS safety chapter are examined here.

Development of accident prediction models has always attracted the interest of traffic safety researchers and is at the forefront of national efforts in road safety research. If a good accident prediction model (SPF) is developed, what are its uses? It can be used in transportation planning for new and existing highways, as a tool to identify problem areas or "sites with promise," or to compare predicted values with observed accident frequency within project limits. Its use, however, does nothing to help with understanding the nature of the problem itself.

Diagnostic investigation into accident causality is necessarily informed by accident diagramming, which is an underappreciated task, yet a critical one. Traditionally, the task of accident diagramming has been assigned to the junior-level technicians and is institutionally undervalued. Its importance, however, cannot be overemphasized. Its benefits are no less significant than the benefits of developing good accident prediction models. When it comes to ramps and ramp-related intersections, accident diagramming should be done by carefully reading accident reports and then plotting accidents and related information on the interchange layout.

PHASE I. SAFETY ASSESSMENT

Figure 1 shows the EIS study region for the I-25–SH-6 freeway area. The overall study area was partitioned into shorter segments, and collision data (covering a 3-year period) for each segment were plotted on appropriate SPF graphs for evaluation: the ordinate value of the plotted points corresponds to the number of accidents occurring within each segment divided by the segment length in miles and the study period in years (APMPY). SPF analysis is done for both total accidents and injury plus fatal collisions.

Figures 2 and 3 show the SPFs (total accidents and severe accidents, respectively) calibrated specifically for six-lane urban freeways together with plotted points representing the observed average 3-year crash history. Segment lengths range between 1 and 1.4 mi.

From Figure 2, it can be observed that all three I-25 sections are LOSS IV (high potential for accident reduction). Because there are so few segments of urban six-lane freeways with continuous auxiliary lanes that carry in excess of 200,000 cars per day in Colorado, it is difficult to predict the expected safety performance with confidence. Even when this uncertainty is taken into consideration, accident frequency in excess of 180 APMPY suggests a high potential for accident reduction, in the authors' opinion. The SH-6 section is performing at the upper bounds of LOSS III and is approaching LOSS IV.

Figure 3 is the SPF graph calibrated for injury and fatal accidents only. The result of this analysis closely approximates that of the total accident analysis shown in Figure 2.

The SH-6 safety problem largely manifests itself in the eastbound direction, exhibiting an accident frequency three times greater than that in the westbound lanes (Figure 4). This unbalanced distribution of accidents suggests significant problems susceptible to correction. It seems that safety performance is heavily influenced by interchange spacing, even though ramp accidents are deleted from the model. The spacing of interchanges, and therefore ramps, on the I-25 and SH-6 study sections is less than that at other urban locations. This is a partial explanation for the elevated accident frequencies in the study area.

The roadway segments were further examined for accident concentrations and patterns. The freeways within the EIS study limits were tested for the presence of accident patterns related to type, severity, direction of travel, road condition, and time of day. Results of the pattern recognition analysis are presented in Figure 4. Pattern recognition analysis was conducted by using methodology described by Kononov (*9*) and Kononov and Janson (*10*). Diagnostic norms are developed with the same data points as those used in generating the SPF. The norms for this type of freeway are presented in Table 2.

In addition to the SPF-LOSS analysis and collision pattern evaluation for the study's freeway segments, an investigation of the involved interchanges was undertaken. Detailed accident diagrams were prepared for the interchange-related intersections. These diagrams substantiate the crash locations and provide descriptive information on the accident type, concentration, and travel direction. Subsequent to accident diagramming, a direct diagnostic analysis was conducted at individual intersections of interest to identify statistically overrepresented crash types. An illustration of the product of this type of focused investigation is presented in Figure 5 for the I-25 and Broadway–Lincoln interchange. Included on the accident diagram are pie charts showing the accident type distribution for each intersection. A significant broadside collision problem is evident at the signalized intersection of the southbound (SB) I-25 off-ramp and Broadway. Thirty-two accidents occurred at this location during the 3-year study

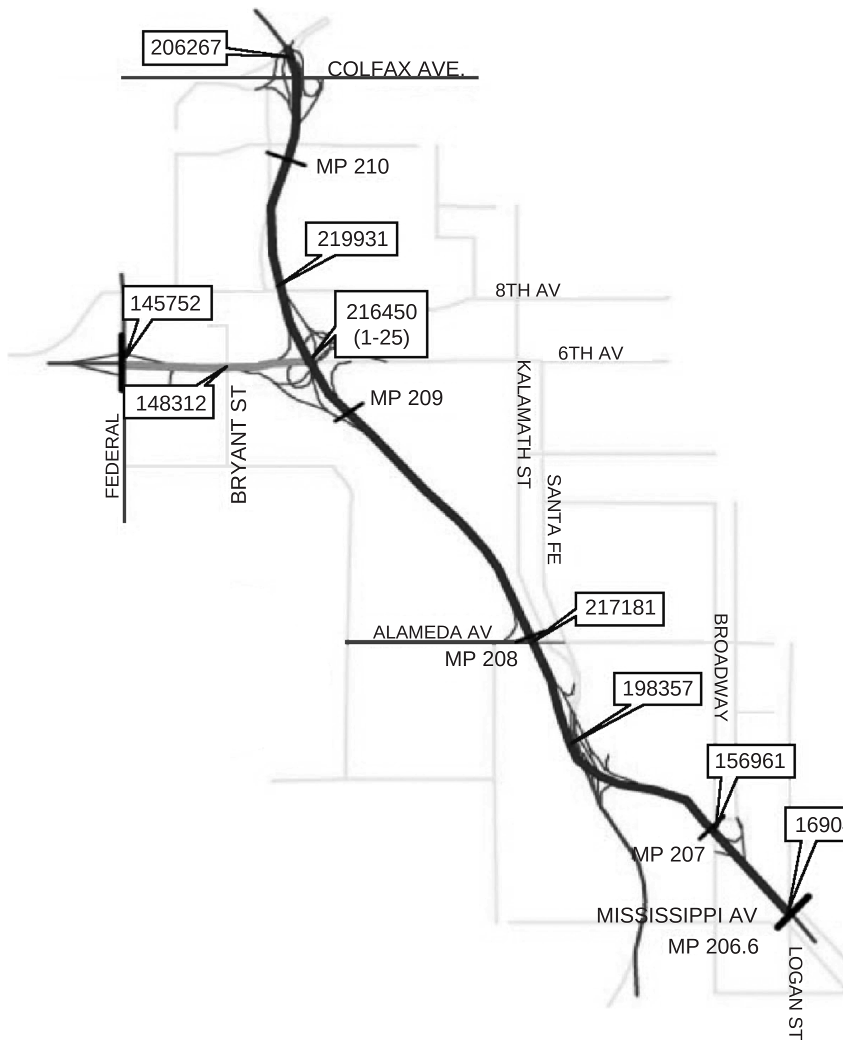

FIGURE 1 EIS study region with AADT.

period, 22 of which were broadsides in the SB direction. These data suggest a signal head visibility problem. During the reconstruction of this intersection, signal heads must be specified and positioned for maximum visibility by drivers.

Approach-turn collisions are a significant problem at the Broadway and Kentucky SB on-ramp. They constitute 63% of the total number of accidents. Same-direction sideswipe accidents also appear to be occurring at a somewhat higher-than-expected frequency. An effective method of preventing approach-turn accidents is to use protected-only phasing for left-turn movements. Same-direction sideswipe accidents can be reduced by providing standard lane width, longer auxiliary lanes, and improved signing, striping, and delineation.

A low-frequency sideswipe pattern is present at the intersection of NB I-25 on- and off-ramps and Lincoln Street. A total of eight accidents occurred here in the 3-year period. Again, the incidence of sideswipe accidents can be reduced by providing standard lane width, longer auxiliary lanes, and improved signing, striping, and delineation.

A low-frequency pattern of single-vehicle accidents developed on the NB I-25 off-ramp. Although only five single-vehicle accidents occurred in this area, the severity of these fixed-object collision and overturning accidents was high, with four of the five accidents resulting in injuries. Providing appropriate warning signs and distinct pavement markings can help motorists judge the ramp curvature and geometry. Future interchange design alternatives will need to consider the high severity of accidents on this ramp.

Summarizing the Phase I investigation, LOSS analysis indicates that the entire section of I-25 in the study area is performing at LOSS IV from the frequency as well as the severity perspective. SH-6 is performing at LOSS III for both frequency and severity. These data suggest a high potential for accident reduction in the study area. Safety problems on I-25 and SH-6 can be related to congestion, recurrent and frequent queuing, close interchange spacing, and the geometric characteristics of the existing I-25 alignment. New alternatives will need to provide better geometrics and improved traffic operations including improved lane balance, ramp metering, full shoulders, and adjusted ramp spacing. Most of the safety problems on interchange ramps can be attributed to congestion and backups on main-line I-25 and SH-6 that result in rear-end and sideswipe same-direction accidents. Accident problems at interchange-related ramp intersections can be addressed by improving traffic signal visibility and sight distance and by implementing protected-only left-turn phases where approach turn problems exist.

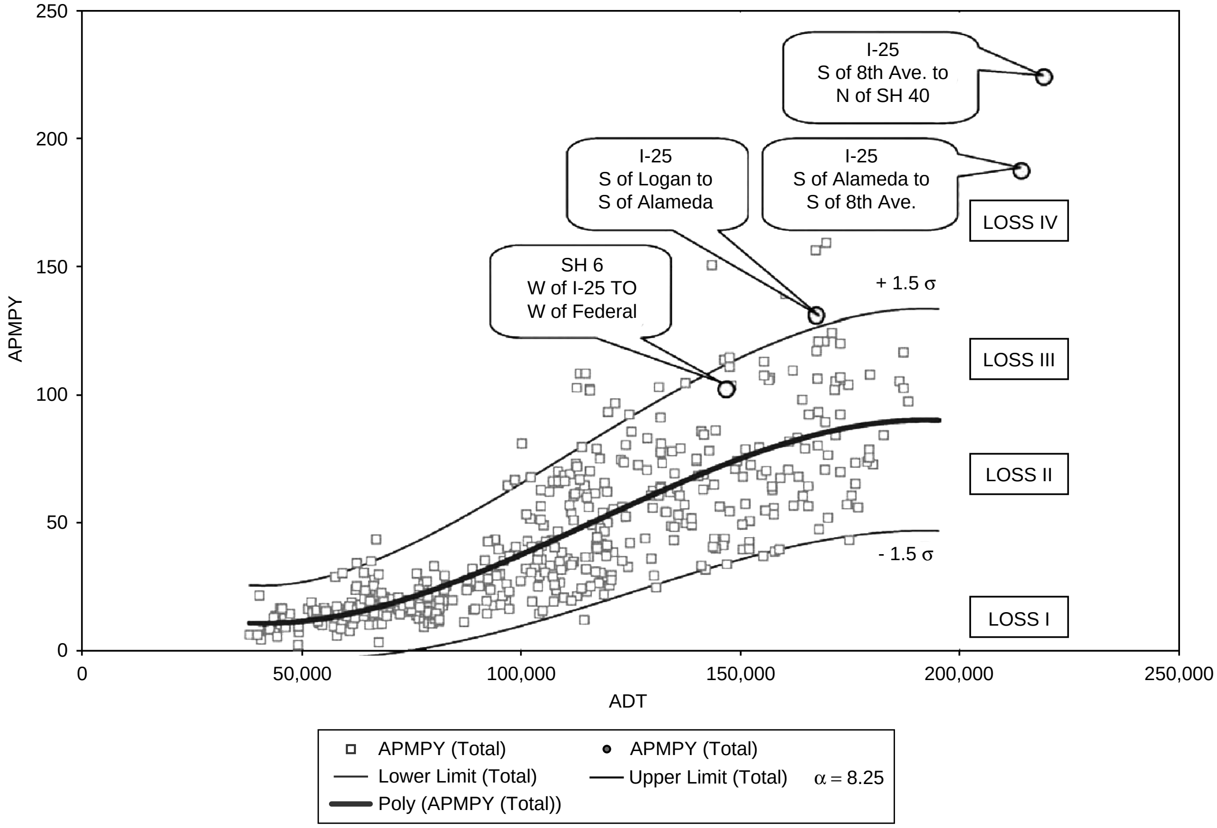

FIGURE 2 Urban six-lane freeway SPF, 1989–2001: total accidents (APMPY = accidents per mile per year; α = 8.25; sections = 0.9 mi).

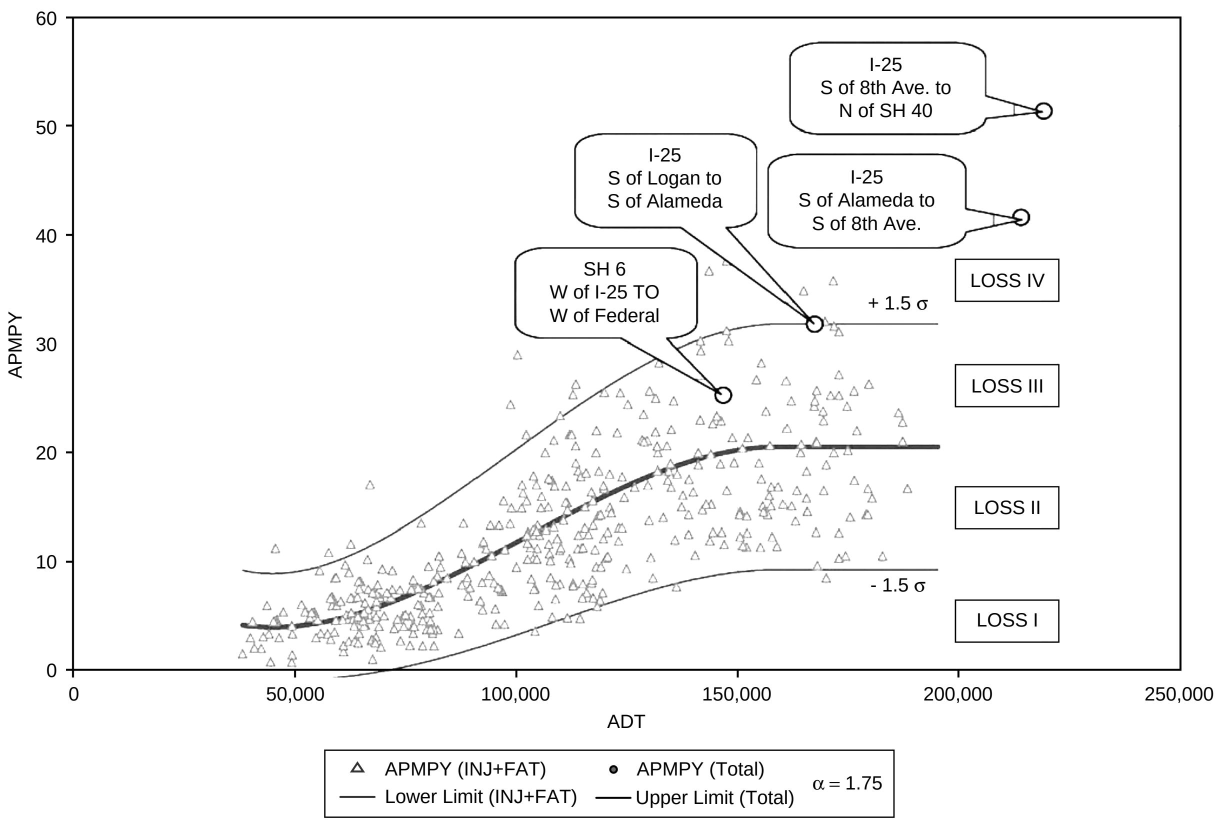

FIGURE 3 Urban six-lane freeway SPF: 1989–2001: injuries plus fatalities only (α = 1.75; sections = 0.9 mi).

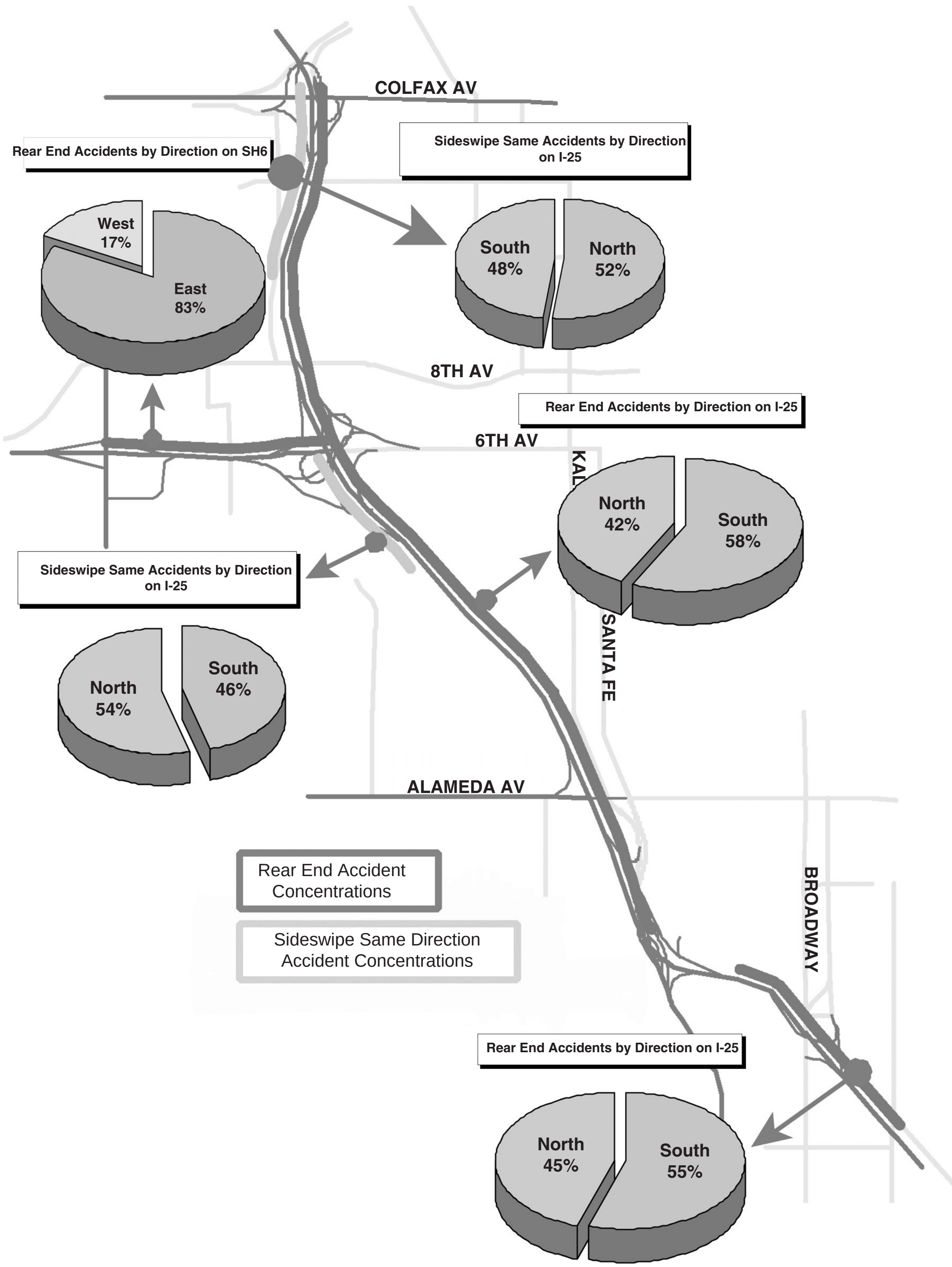

FIGURE 4 Results of pattern recognition analysis.

TABLE 2 Diagnostic Norms for Urban Six-Lane Freeways

Description	Percent	Description	Percent	Description	Percent
PDO	71.14	Daylight	68.75	Wild animal	0.44
INJ	28.49	Dawn or dusk	3.79	Light or utility pole	1.40
FAT	0.36	Dark—lighted	19.58	Traffic signal pole	0.04
Single vehicle accidents	21.23	Dark—unlighted	5.91	Sign	0.87
Two vehicle accidents	59.61	Unknown lighting	1.97	Bridge rail	0.36
Three or more vehicle accident	19.00	No adverse weather	81.12	Guardrail	3.85
Unknown number of vehicles	0.16	Rain	6.61	Median barrier	8.61
On road	77.55	Snow, sleet, or hail	9.72	Bridge abutment	0.11
Off road	21.63	Fog	0.21	Column or pier	0.06
Off road left	11.02	Dust	0.01	Culvert or headwall	0.07
Off road right	10.45	Wind	0.32	Embankment	0.36
Off road at tee	0.04	Unknown weather	2.00	Curb	0.47
Off road in median	0.12	Overturning	2.74	Delineator post	0.47
Unknown road location	0.82	Other noncollision	1.48	Fence	0.83
Dry road	75.53	School-age pedestrians	0.05	Tree	0.21
Wet road	10.24	All other pedestrians	0.17	Large boulder	0.03
Muddy road	0.07	Broadside	1.29	Rocks in roadway	0.05
Snowy road	2.83	Head on	0.23	Barricade	0.17
Icy road	6.37	Rear end	50.27	Wall or building	0.19
Slushy road	1.82	Sideswipe (same direction)	18.78	Crash cushion	0.30
Foreign material road	0.13	Sideswipe (opposite direction)	0.20	Mailbox	0.01
With road treatment	0.20	Approach turn	1.10	Other fixed object	0.26
Dry with icy road treatment	0.04	Overtaking turn	0.35	Involving other object	1.79
Wet with icy road treatment	0.05	Parked motor vehicle	1.47	Road maintenance equipment	0.10
Snowy with icy road treatment	0.05	Railway vehicle	0.00	Unknown accident type	0.75
Icy with icy road treatment	0.09	Bicycle	0.03	Total fixed objects	18.68
Slushy with icy road treatment	0.02	Motorized bicycle	0.00	Total other objects	1.93
Unknown road condition	2.55	Domestic animal	0.03	Total accidents	23,849

NOTE: Bold lines depict groupings for purposes of discussion.

PHASE II. ALTERNATIVES

Main Line I-25

The preferred design alternative will provide the following improvements to enhance main-line safety:

- Lane balance,
- Ramp metering, and
- Full shoulders throughout the study area and standard acceleration and deceleration at every ramp.

By providing lane balance in concert with full shoulders, standard auxiliary lanes, and ramp metering, a composite accident reduction of 20% can be achieved on the main line. This conservative estimate was developed on the basis of observational before-and-after studies in Colorado.

An estimate of the long-term accident savings potentially available following implementation of the main-line improvements can be determined. Assuming a 2% annual growth in the number of accidents associated with increasing traffic volume over the next 20 years, the expected number of accidents prevented is shown in Table 3.

It is estimated that the 20-year expected accident reduction would be in the range of 9,840 to 10,240 total accidents. Of those, 2,230 to 2,420 would be prevented injuries.

I-25 at Broadway–Lincoln Interchange

In Phase I the following problems were identified: broadside accidents are overrepresented at the SB off-ramp intersection and approach-turn accidents are overrepresented at the Kentucky–SB on-ramp intersection. To achieve a maximum safety benefit from reconstruction of this interchange, these problems should be addressed and corrected by the preferred alternative.

The I-25 and Broadway–Lincoln preferred Alternative 3 geometry is shown in Figure 6. The safety benefits gained from this alternative will primarily be through the implementation of revised signal phasing, increased visibility of signal heads, and improved lane geometry. The potential safety improvements are summarized as follows:

- With intersection improvements, the frequency of broadside accidents will be reduced by 50% at the SB off-ramp intersection;
- With intersection improvements, the frequency of approach-turn accidents will be reduced by 70% at the Kentucky–SB on-ramp intersection; and

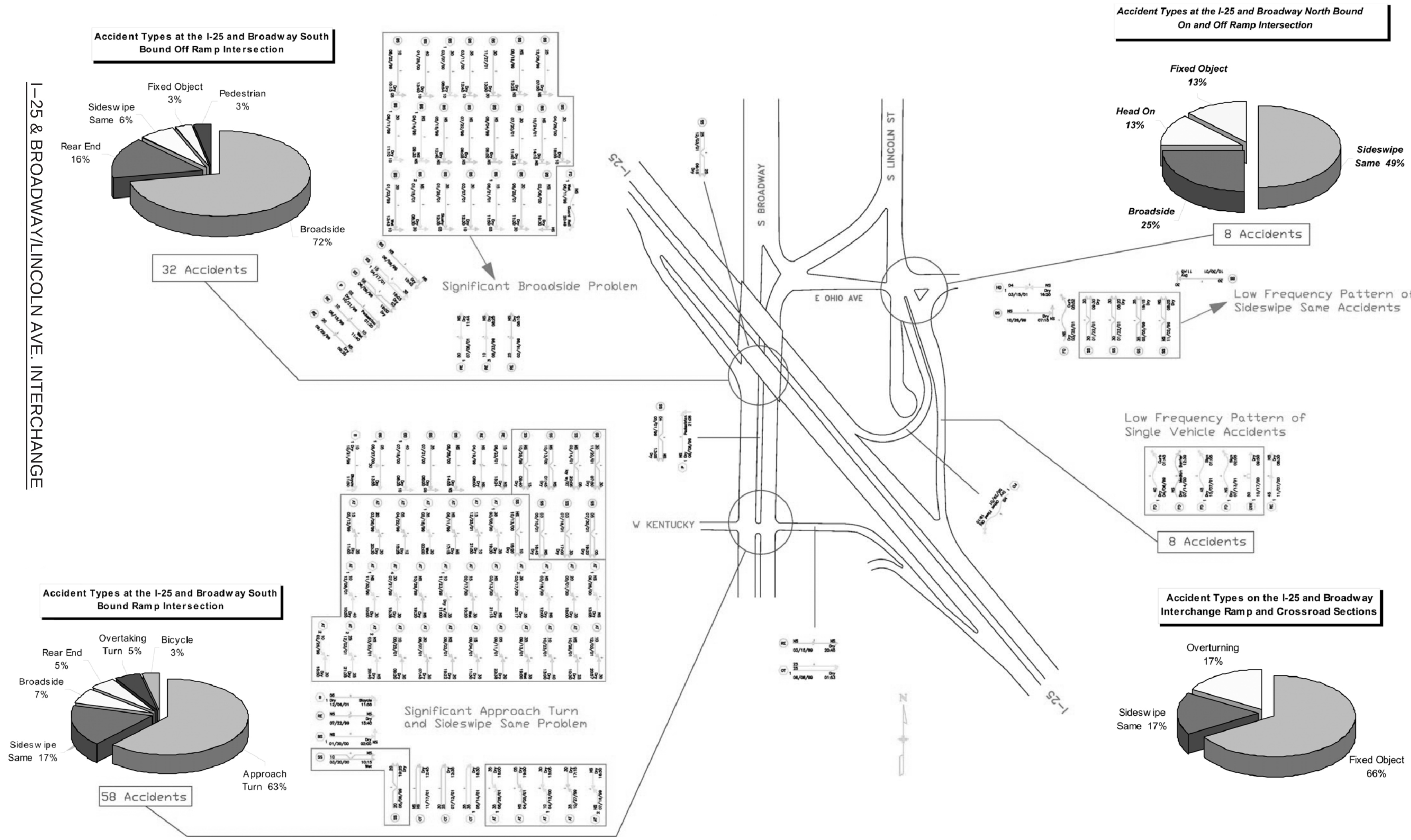

FIGURE 5 Accident diagrams at interchange-related intersections.

TABLE 3 Expected Reduction in Accidents: Main Line I-25

Year	Accidents	Year	Accidents	Year	Accidents	Year	Accidents
1	413	6	456	11	503	16	556
2	421	7	465	12	514	17	567
3	430	8	474	13	524	18	578
4	438	9	484	14	534	19	590
5	447	10	494	15	545	20	602

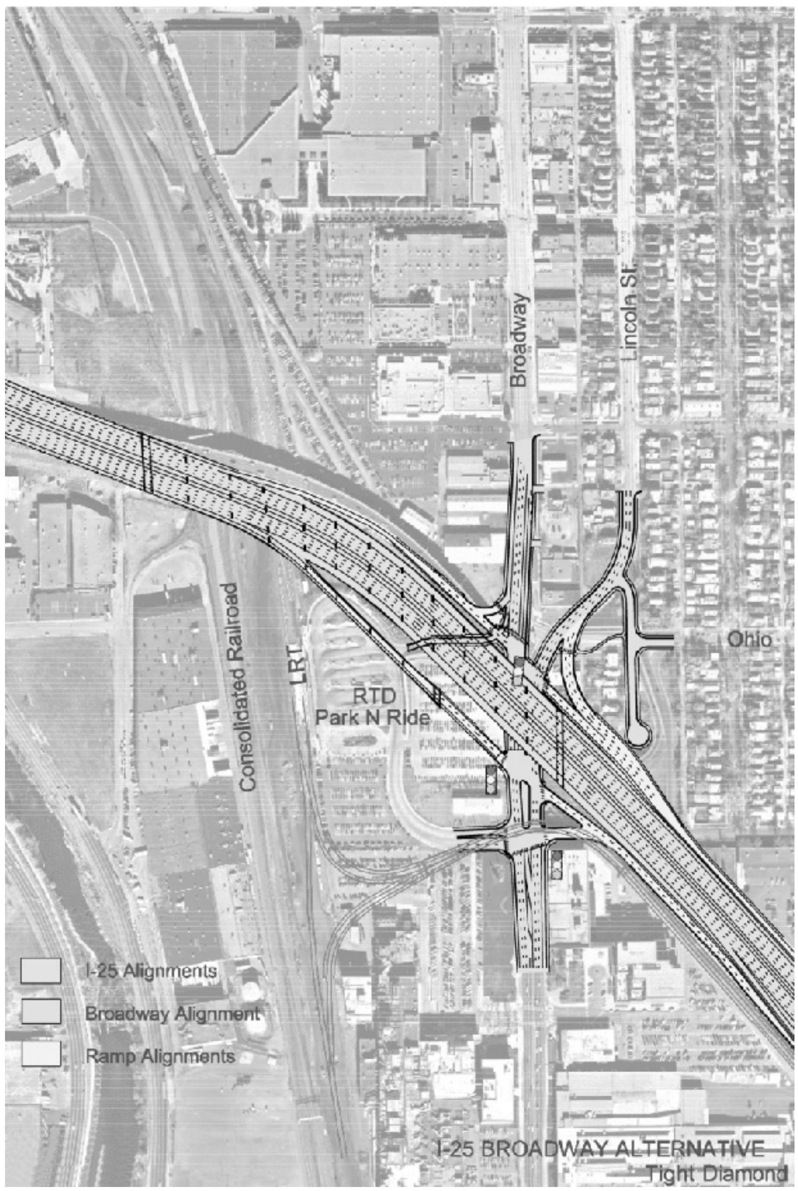

FIGURE 6 I-25 and Broadway–Lincoln preferred Alternative 3 geometry.

TABLE 4 Expected Reduction in Accidents: I-25 Broadway–Lincoln Interchange

Year	Accidents	Year	Accidents	Year	Accidents	Year	Accidents
1	15	6	17	11	18	16	20
2	15	7	17	12	19	17	21
3	16	8	17	13	19	18	21
4	16	9	18	14	19	19	21
5	16	10	18	15	20	20	22

- With intersection and geometric enhancements, the frequency of same-direction sideswipe accidents will be reduced by 80% at the Kentucky–SB on-ramp intersection.

In a manner similar to the main-line forecast, the potential crash savings linked to the preferred interchange improvements can be estimated. By assuming a 2% annual growth in the number of accidents accompanying increasing traffic volume over the next 20 years, the expected reduction in accidents is shown in Table 4. The 20-year expected accident reduction is estimated to be in the range of 330 to 400 total accidents. Of those, 70 to 100 would be prevented injuries.

CONCLUSIONS

A two-phase process to explicitly evaluate the safety impacts of multiple design alternatives within the scope of a transportation planning study has been developed. Phase I will accomplish the following:

- Assess the magnitude and nature of safety problems within study limits;
- Relate crash causality to roadway geometrics, roadside features, traffic control devices, traffic operations, driver behavior, and vehicle type;
- Suggest cost-effective countermeasures to address identified problems; and
- Provide guidance on identifying the preferred alternative from a safety standpoint.

Throughout Phase I, SPFs, diagnostic menus, pattern recognition analysis, and accident diagramming are used in concert with site visits and plan reviews. It was found that the use of accident diagramming to aid in diagnostic analysis is essential for effective countermeasure development, particularly in complex urban environments.

Phase II quantifies how well each design alternative addresses safety problems identified in Phase I. The extent to which an alternative resolves these problems is quantified by its estimated accident reduction, which in turn is based on the nature and magnitude of existing safety problems and their susceptibility to correction. These accident reduction estimates are inherently associated with some degree of uncertainty, yet it is believed that this approach will allow identification of design alternatives that are safer than others.

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