Relationships Between Safety and Both Congestion and Number of Lanes on Urban Freeways

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This paper first explores the relationship between safety and congestion and then examines the relationship between safety and the number of lanes on urban freeways. The relationship between safety and congestion on urban freeways was explored with the use of safety performance functions (SPFs) calibrated for multilane freeways in Colorado, California, and Texas. The focus of most SPF modeling efforts to date has been on the statistical technique and the underlying probability distribution, with only limited consideration given to the nature of the phenomenon itself. In this study neural networks have been used to identify the underlying relationship between safety and exposure. The modeling process was informed by the consideration of the traffic operations parameters described by the *Highway Capacity Manual.* The shape of the SPF is best described by a sigmoid reflecting a dose–response type of relationship between safety and traffic demand on urban freeways. Relating safety to the degree of congestion suggests that safety deteriorates with the degradation in the quality of service expressed through the level of service. Practitioners generally believe that additional capacity afforded by additional lanes is associated with more safety. How much safety and for what time period are generally not considered. Comparison of SPFs of multilane freeways suggests that adding lanes may initially result in a temporary safety improvement that disappears as congestion increases. As annual average daily traffic increases, the slope of SPF, described by its first derivative, becomes steeper, reflecting that accidents are increasing at a faster rate than would be expected from a freeway with fewer lanes.

Two roads diverged in a wood, and I—
I took the one less traveled by,
And that has made all the difference.
(From "The Road Not Taken," by Robert Frost)

The relationship between safety and congestion on urban freeways was explored by examining the shape of the safety performance functions (SPF). SPFs are accident prediction models that relate traffic exposure, measured in annual average daily traffic (AADT), to safety, measured in the number of accidents over a unit of time [accidents per mile per year (APMPY)].

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Review of extant literature on the development of SPF suggests that the focus of most modeling efforts is on the statistical technique and underlying probability distribution. Poch and Mannering (*1*) concluded that the negative binomial regression is a powerful predictive tool and should be increasingly applied in future accident frequency studies.

Shankar et al. (*2*) used both the Poisson and negative binomial distributions to evaluate the effects of roadway geometrics and environmental factors on rural accident frequency in Washington State. They used negative binomial assumptions when data were overdispersed and Poisson when not.

Abdel-Aty and Radwan (*3*) observed that most of the accident data are overdispersed, a condition that points to the need for a correction to Poisson assumptions, and correctly concluded that the negative binomial formulation is superior to the more restrictive Poisson formulations.

Miaou (*4*) suggested that Poisson model assumptions should be used to establish an initial relationship between highway data and accidents, and if overdispersion is found, a negative binomial regression model can be explored.

Lord et al. (*5*) concluded that Poisson and negative binomial models serve as statistical approximation to the crash process. Poisson models serve well under nearly homogeneous conditions, while negative binomial models serve better in all other cases. Lord et al. also suggested that it may be preferable to begin to develop models that consider the fundamental process of a crash and to avoid striving for best-fit models in isolation.

There is clearly a consensus among researchers that underlying randomness is well described by the Poisson or negative binomial distributions. The underlying phenomenon itself, however, is not well understood.

Harwood concluded the following:

> It would be extremely valuable to know how safety varies with V-C ratio and what V-C ratios provide minimum accident rate. Only limited research has been conducted on the variation of safety with V-C [volume–capacity] ratio. More research of this type is needed, over a greater range of V-C ratios, to establish valid relationships between safety and traffic congestion to provide a basis for maximizing the safety benefits from operational improvement projects. (*6*)

Hall and Pendleton observed that

> the implication of the existence of a definite relationship between traffic accident rates and the ratio of current or projected traffic volume to capacity is quite significant. Knowledge of any such relationship would help engineers and planners assess the safety implications both of projected traffic growth on existing highways and of highway improvements designed to increase capacity. (*7*)

To date, the focus of modeling efforts has been on random variability, with only a limited consideration of a systemic component. Selection of the functional form is heavily influenced by the choice of functions available in the software package used by the modeler. Accidents on an urban freeway are a byproduct of traffic flow; therefore, observing changes in the flow parameters may give clues about the probability of accident occurrence and changes in accident frequency. Hauer (*8*) observed that there is no reason to think that an underlying phenomenon follows any simple mathematical function. Use of the neural networks in this study offers an opportunity to explore the underlying relationship between variables without being limited by a preselected mathematical function. Neural networks are not constrained by the underlying distributional assumptions and learn by example, inferring a model from training data. In this study, traffic operations parameters described in the *Highway Capacity Manual* (HCM) (*9*) were used to inform the SPF development process.

DATA SET PREPARATION AND MODEL DEVELOPMENT

Five years of accident data from California, Colorado, and Texas were used to develop SPFs for selected multilane urban freeways. California data were obtained from the Highway Safety Information System; data sets for Colorado and Texas were provided by their departments of transportation. All the accidents that occurred on ramps and crossroads were removed before fitting the models, which left only accidents occurring on the freeway mainline itself. Two kinds of SPFs were calibrated for Colorado and California: one for the total number of accidents and the other for crashes involving injury or fatality. Due to data availability, only total-accident SPF models were calibrated for Texas.

SPFs were developed by using neural networks, a subset of a general class of nonlinear models. Neural network were used to analyze the data, which consisted of observed, univariate responses Y_i known to be dependent on a corresponding one-dimensional inputs x_i. Neural networks are not constrained by a preselected functional form and specific distributional assumptions. For our application, Y_i = APMPY and x_i = AADT. The model becomes

$$Y_i = f(x_i, \theta) + e_i$$

where

$f(x_i, \theta)$ = nonlinear function relating Y_i to independent variable Y_i for the ith observational unit,
θ = p-dimensional vector of unknown parameters, and
e_i = sequence of independent random variables.

The goal of the nonlinear regression analysis is to find the function f that best reproduces the observed data. A form of the response function used in many engineering applications is a feed-forward neural network model with a single layer of hidden units. The form of the model is

$$f(x, \theta) = \beta_0 + \sum_{k=1}^{K} \beta_k \varphi(x\gamma_k + \mu_k)$$

where

$\varphi(u) = e^u/(1 + e^u)$ = logistic distribution function,
β_k = connection weights,
$\beta_0, \beta_1, \gamma_1, u_1$ = parameters to be estimated,
μ_k = biases [Ripley (*10*)], and
K = number of hidden units.

The function f is a very flexible nonlinear model used in this application to capture the overall shape of the observed data. The function $\varphi(u)$ is a logistic distribution function. When $K = 1$, there is one hidden unit. In this case, the function performs a linear transformation of the input x and then applies the logistic function $\varphi(u)$, followed by another linear transformation. The overall result is a very flexible nonlinear model.

The parameter vectors β_0, β_1, γ_1, and u_1 for each data set are unknown and will be estimated by nonlinear least squares. The complexity for this application is the number of hidden units K in the model. $K = 1$ was chosen on the basis of the general understanding of the underlying physical phenomenon. Additionally, the complexity of the model is most often chosen on the basis of the generalized cross-validation model selection criterion. Cross-validation is a standard approach for selecting smoothing parameters in nonparametric regression described by Wahba (*11*). Figures 1 through 4 represent total crash SPFs and model fit information for the selected multilane freeways in Colorado, California (two figures), and Texas. The R^2 parameter, predicted values from the model versus the residuals and the root mean squared error are also given. The residuals exhibit a pattern of increased variance as the AADT values increase. This is to be expected given the overall pattern of the data. Overall model fit to the data is quite reasonable.

SPFs for multilane freeways in different states are different due to different reporting thresholds, climate, and other local factors, yet sigmoid functional shapes of the SPFs generated by the neural network regression are similar. The shape reflects a relationship similar to a dose–response curve found in medicine and pharmacology, as well as in other sciences. In all cases, accident data for urban freeways exhibited extra variation or overdispersion relative to the Poisson model.

RELATING CHANGES IN ACCIDENT RATES WITH CHANGES IN SHAPE OF SPF: BRIEF OVERVIEW

Accident rates change with AADT, and SPF reflects how these changes take place. Higher rates within the same SPF mean less safety than lower rates. Any accident frequency derived from the SPF expressed in APMPY can be easily converted into accident rates measured in accidents per million vehicle miles traveled (acc/MVMT). For instance, the Colorado SPF calibrated for six-lane urban freeways (Figure 5) with 120,000 AADT is expected to produce on average 56 APMPY, which can be directly converted to the accident rates as follows:

$$\frac{(56 \text{ acc/mile/year}) \times 1{,}000{,}000}{120{,}000 \text{ vpd} \times 1 \text{ mile} \times 365 \text{ days/year}} = 1.28 \text{ acc/MVMT}$$

Changes in the accident rates are reflected by the shape of the safety performance function. It is assumed that Points A and B in Figure 6 are values from F_i, an SPF representing a multilane freeway. Then, accident rate at AADT_A (R_A) and at AADT_B (R_B) can be expressed as follows:

$$R_A = \frac{A}{\text{AADT}_A} * C$$

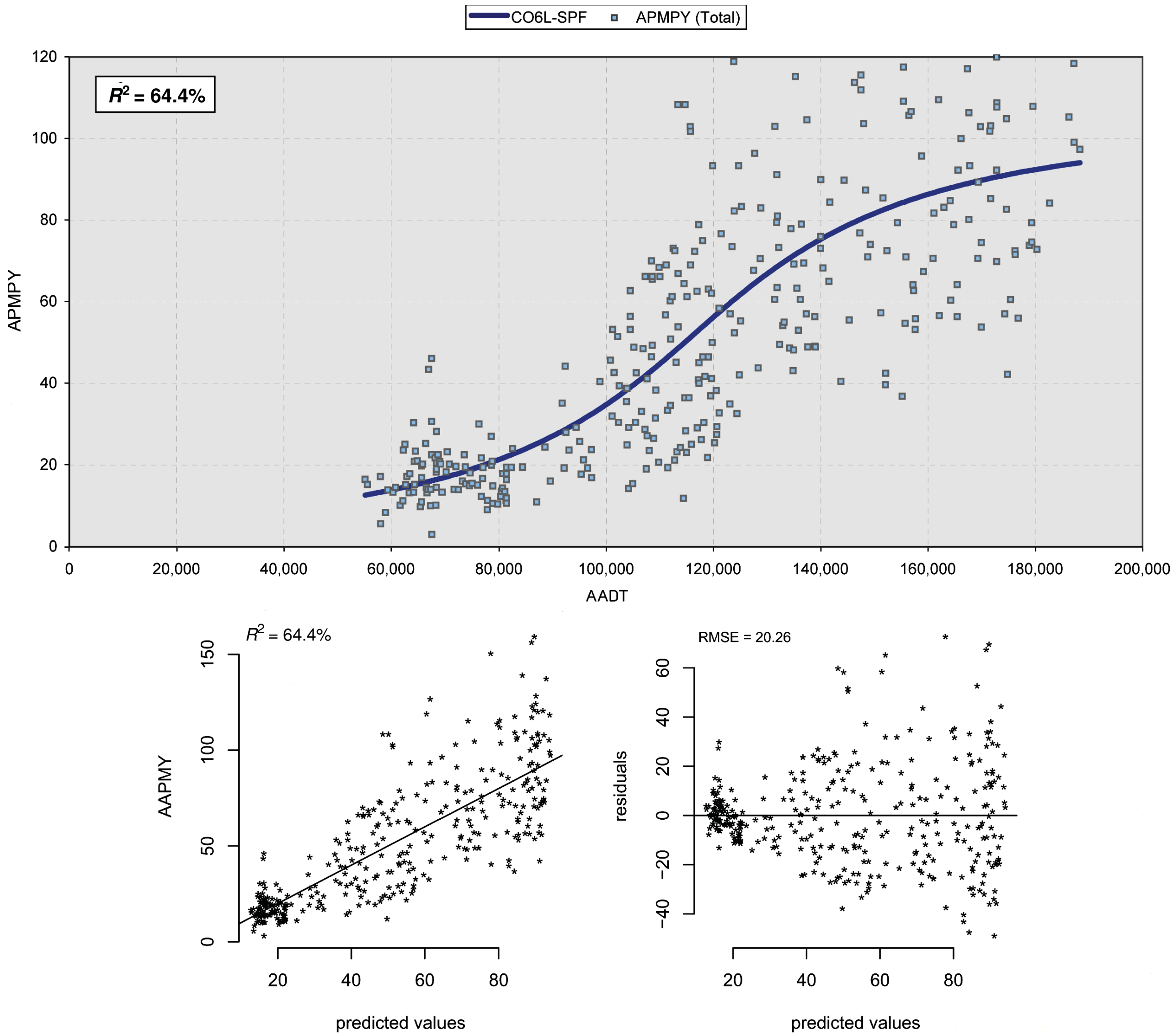


FIGURE 1 Colorado six-lane freeway SPF and model fit information.

$$R_B = \frac{B}{\text{AADT}_B} * C$$

$$C = \frac{1{,}000{,}000}{1 \text{ mi} * 365 \text{ days/year}}$$

As the transition is made from Point A to Point B, the number of accidents is increasing with AADT; however, the accident rate itself can remain the same, decrease, or increase depending on the shape of the SPF. Figure 6 graphically represents each scenario and is explained here:

1. Rate at A = rate at B.

if
A and $B \in F_i$ and

$$\frac{A}{\text{AADT}_A} = \frac{B}{\text{AADT}_B} \Rightarrow R_A = R_B$$

In this case, as a transition is made from Point A to Point B of the SPF, the accident rate at A is the same as the accident rate at B. The number of accidents is increasing with AADT in such a way that the ratio of crashes to exposure at Points A and B is preserved. This change is reflected by a relatively moderate gradient in the shape of the function.

2. Rate increases

if
A and $B \in F_i$ and

$$\frac{A}{\text{AADT}_A} < \frac{B}{\text{AADT}_B} \Rightarrow R_A < R_B$$

In this case, as a transition is made from Point A to Point B of the SPF, the accident rate is increasing. The number of accidents increases with AADT in such a way that the ratio of crashes to exposure is increased. This change is reflected by a relatively steep gradient in the shape of the function.

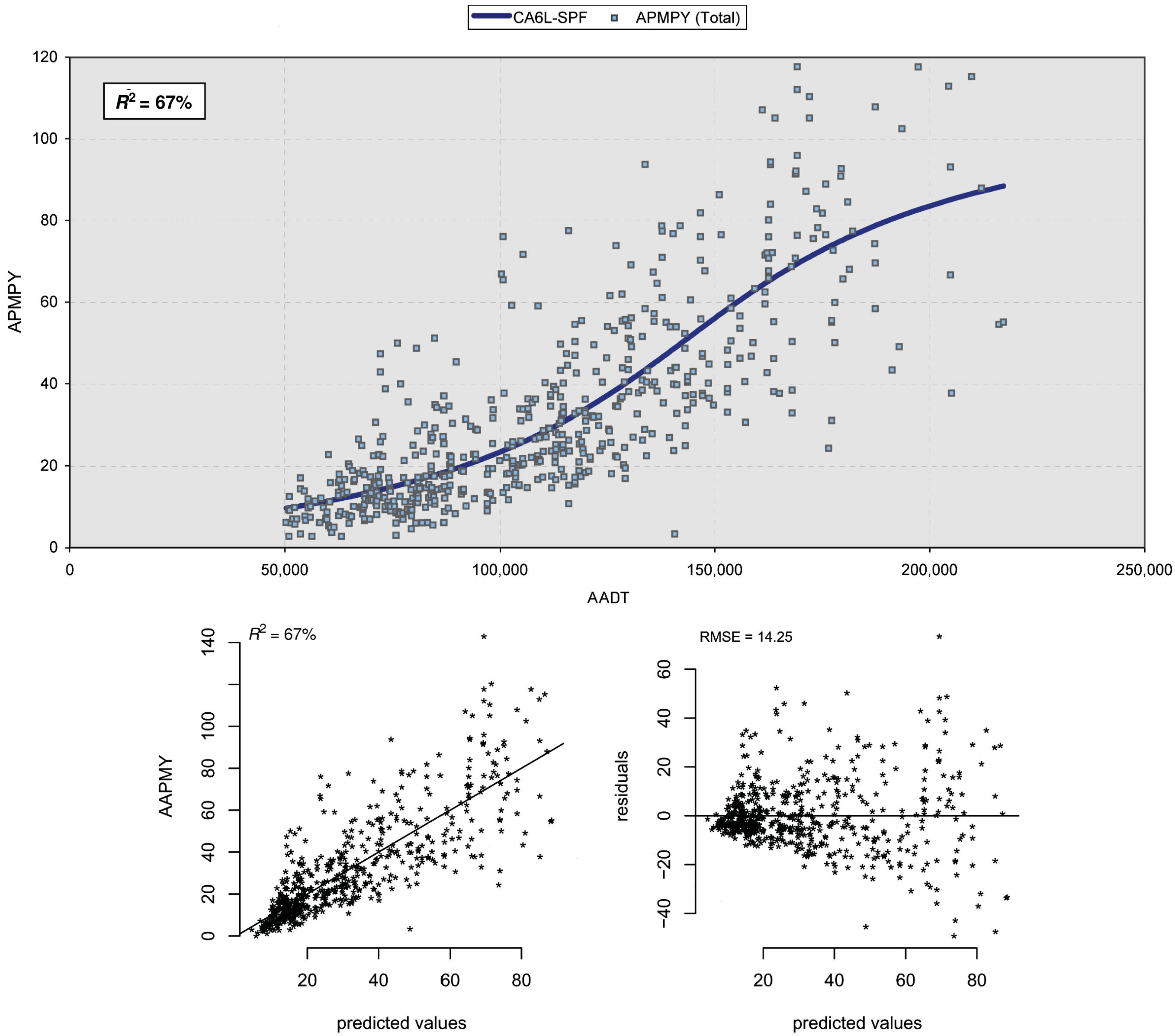


FIGURE 2 California six-lane freeway SPF and model fit information.

3. Rate decreases

if
A and $B \in F_i$ and

$$\frac{A}{\mathrm{AADT}_A} = \frac{B}{\mathrm{AADT}_B} \Rightarrow R_A > R_B$$

In this case, as a transition is made from Point A to Point B of the SPF, the accident rate is decreasing. The number of accidents is increasing with AADT, but AADT is increasing faster. It is reflected by a very mild upward gradient of the SPF.

Figure 7 shows changes in accidents rates observed on six-lane urban Colorado freeways from the low to high range of AADT. For the SPF representing total crashes the accident rate is more than doubled as a transition is made from 60,000 to 150,000 AADT.

For the injuries and fatal-crashes SPF, the accident rate increases from 0.23 accidents per MVMT to 0.37 accidents per MVMT (an increase of 65%) as AADT increases from 60,000 to 150,000. The sigmoid functional shape of the SPF has two critical points at which the rate of change in the gradient of the function is significantly altered. These points were located by using a sliding interval analysis in the framework of the numerical differentiation technique described by Rao (*12*).

RELATING CHANGES IN FREEWAY FLOW PARAMETERS WITH CHANGES IN ACCIDENT RATES REFLECTED BY SHAPE OF SPF

In an effort to relate freeway flow parameters such as speed (v) and density (d) during the peak period associated with the changes in the shape of the SPF, HCM (*9*) methodology was used. The

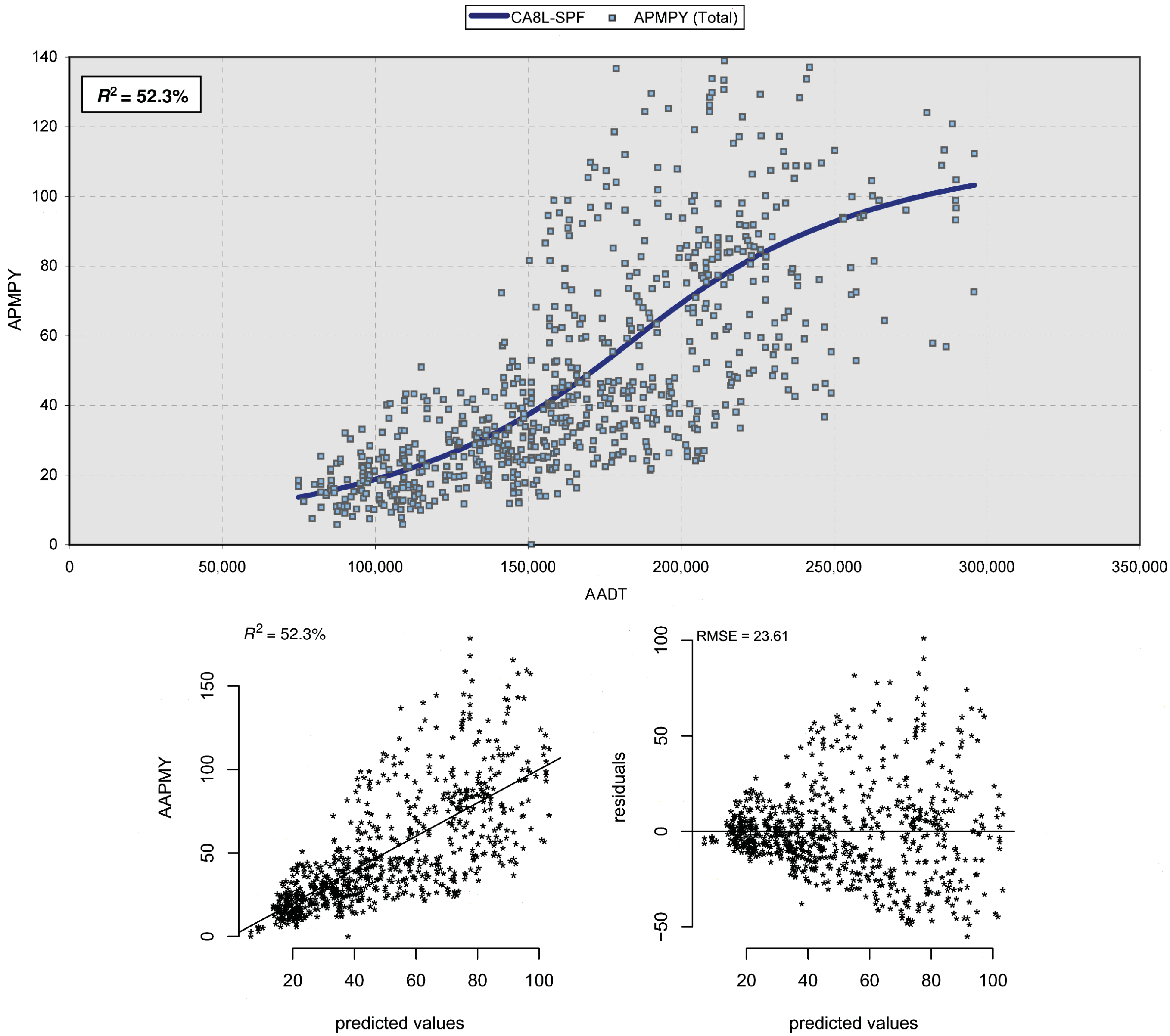


FIGURE 3 California eight-lane freeway SPF and model fit information.

following assumptions typical of the urban freeway environment were used:

- Design hourly volume (DHV) = 10% of AADT for AADT < 130,000,
- DHV = 8% of AADT for AADT > 130,000,
- Peak-hour factor = 0.9,
- Percentage of trucks during peak period = 2%,
- Terrain = level,
- Lane width = 12 ft,
- Shoulder width > 6 ft, and
- Interchange spacing = one interchange per mile.

The results of the HCM analysis were superimposed onto the SPF and are presented in Figure 8. Traffic density at 90,000 AADT is a critical point on the SPF and can be viewed as a critical density beyond which accidents increase at a faster rate. The portion of the SPF to the left of critical density can be viewed as a subcritical zone, at which accidents increase gradually with AADT. Traffic density at 150,000 AADT can be viewed as a supercritical density, beyond which accidents increase very gradually with AADT and accident rates level off or even decline. The portion of SPF to the right of supercritical density can be viewed as a supercritical zone. The portion of the SPF between critical and supercritical densities can be termed a transitional zone.

In Figure 8, as AADT increases from 60,000 to 90,000, traffic density increases by 50% [from 16 passenger cars per mile per lane (pc/mi/ln) to 24 pc/mi/ln], while operating speeds remain almost the same (70 and 69 mph). It is not unreasonable to assume that, if operating speeds remain high and traffic density is increased by 50%, accident probability is also increased. The freeway environment becomes much less forgiving of driving errors and road rage–like

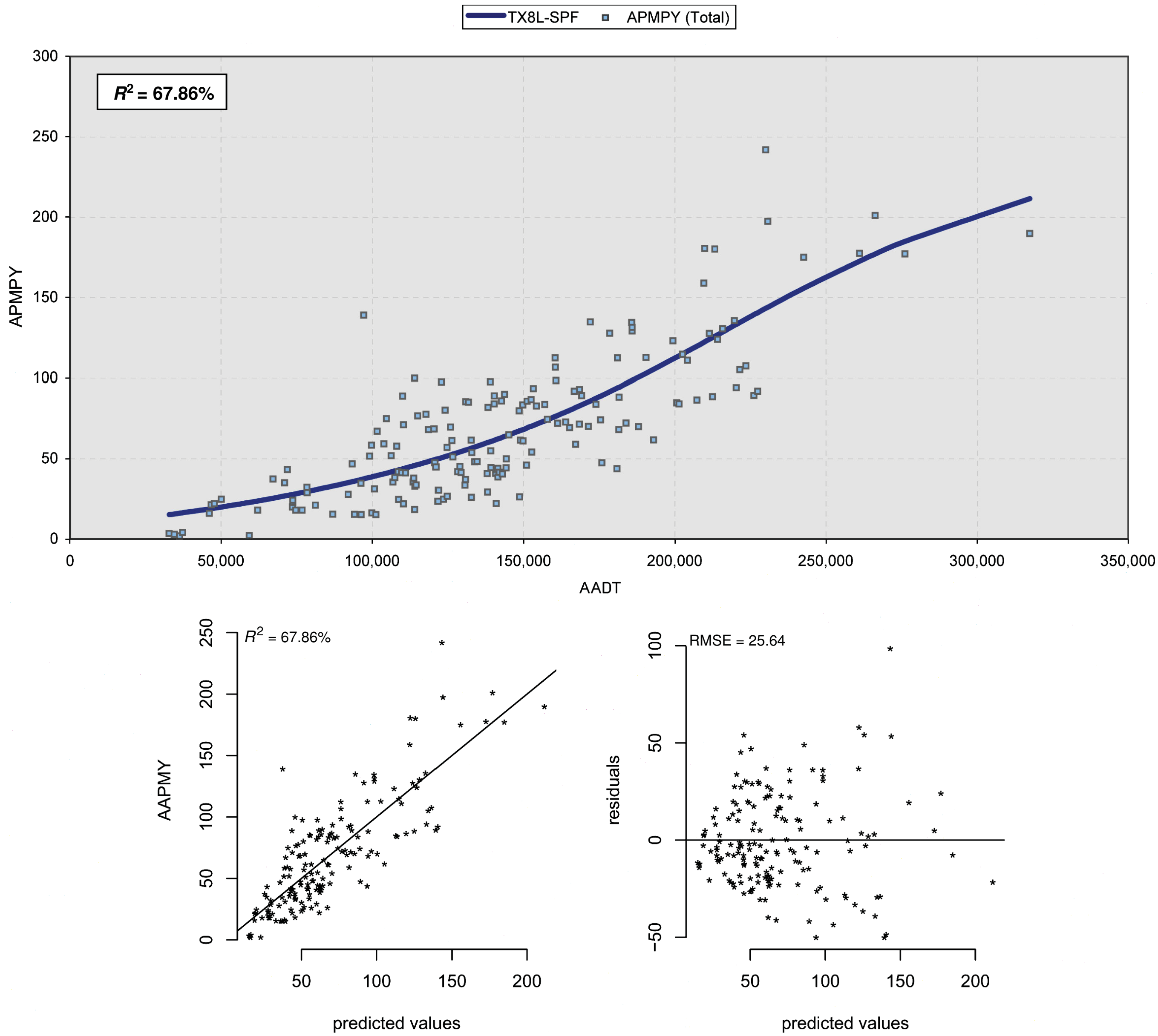


FIGURE 4 Texas eight-lane freeway SPF and model fit information.

behavior with an increase in traffic density at freeway speeds. The SPF reflects that past an AADT of 90,000 the number of crashes increases at a much faster rate with an increase of AADT.

A possible explanation is that traffic has reached some critical density beyond which notably higher accident rates are observed. This increase in the rates is manifested by the steeper gradient of the SPF.

Examination of the SPF, in concert with traffic operations parameters, suggests that, when freeways are not congested and traffic density is low, the number of crashes increases only moderately with an increase in traffic. That is why initially the slope of the SPF is relatively flat; however, once critical density is reached, the number of crashes begins to increase at a much faster rate with increase in traffic. Attainment of the critical density can be viewed as a critical mass–like phenomenon in physics. Mix of density and speed of traffic is such that the probability of a crash is substantially increased, thus a steep reach of the SPF.

Further examination of SPF suggests that past the point of supercritical density (AADT of 150,000) the function begins to level off, reflecting only a moderate increase in accidents and a decrease in accident rates related to a high degree of congestion and a significant reduction in operating speeds. Density exceeds 45 vehicles per mile per lane, and speeds are below 52 mph, which corresponds to a level of service (LOS-F).

Figures 9 and 10 show the boundaries of the LOS during the peak period superimposed onto the SPFs for the total and injury and fatal crashes. The LOS boundaries during peak periods were estimated by using the HCM under the same default assumptions as earlier. Average accident rates for the total and injury and fatal crashes were computed for each LOS and are also provided in Figures 9 and 10.

Integration of LOS and accident rates into the SPF framework permits safety to be quantitatively related to the degree of congestion. The data show that total as well as injury and fatal crash rates

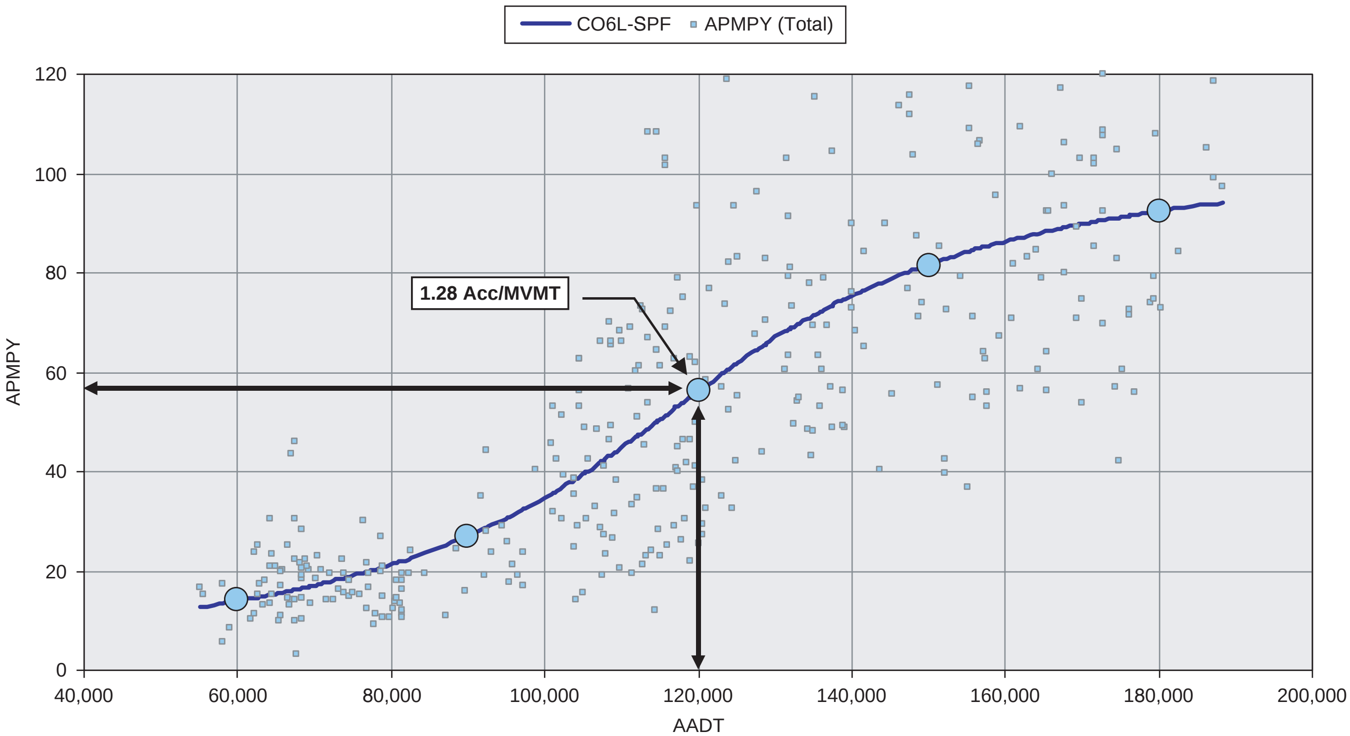


FIGURE 5 Colorado SPF: six-lane urban freeways, accident rates, and frequency per mile per year.

increase with AADT and that it is significantly safer to travel on urban freeways that operate at LOS-C or better during the peak period than on more congested facilities. This knowledge has important implications on the philosophy and policy of transportation planning and highway design criteria.

RELATING SAFETY TO NUMBER OF LANES

Decisions to add travel lanes on a freeway are motivated by the need to provide capacity. It is generally believed by practicing engineers and planners that decreased congestion is associated with some degree of improved safety, yet the majority opinion among researchers is that accident rates increase with an increase in the number of lanes. Some studies, however, have found that the opposite is true.

From the HCM (*9*), it is known that capacity is increased proportionally with the number of lanes, with some adjustment for an increase in the free-flow speed as the number of lanes increases. What effect the number of lanes has on safety, however, is not fully understood.

Research conducted by Council and Stewart (*13*) on the safety effects of converting two-lane roads to four lanes found a 40% to 60% reduction in crashes as a result of conversion to four-lane cross section.

Milton and Mannering (*14*) found that increasing the number of lanes in rural Washington State led to more accidents.

Noland and Oh (*15*) rejected the hypothesis that geometric improvements, including increase in the number of lanes, lane width, median width, and reduction in curvature, are beneficial for safety.

Abdel-Aty and Radwan (*3*) observed that crash rates increased with number of lanes on urban roadway sections.

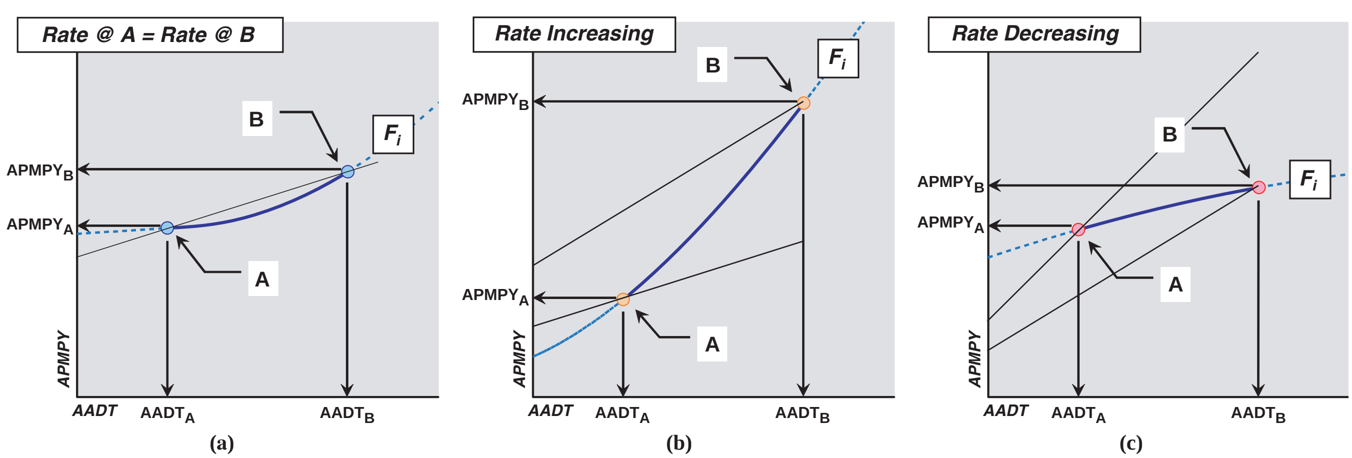


FIGURE 6 Changes in accident rate within SPF: (*a*) rate at Point A equal to rate at Point B, (*b*) rate increasing, and (*c*) rate decreasing.

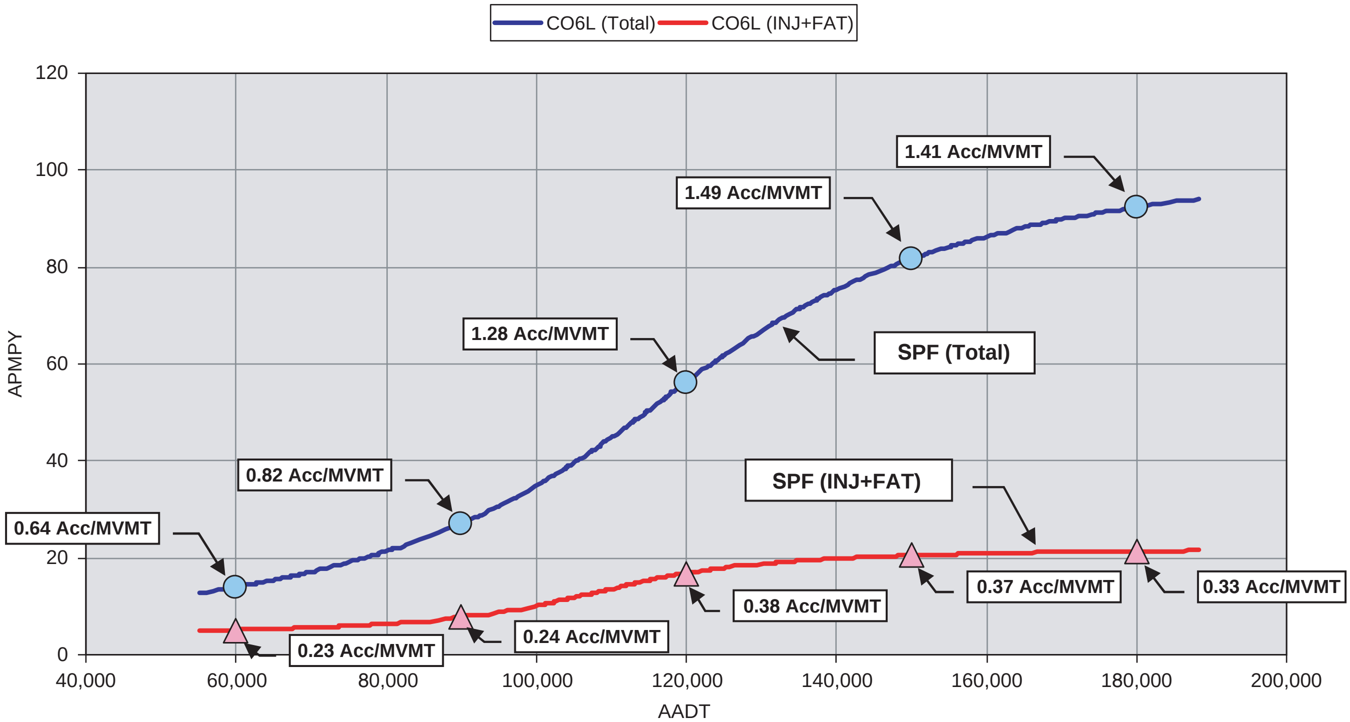


FIGURE 7 Changes in accident rates within SPF (total accidents and injury and fatal crashes only).

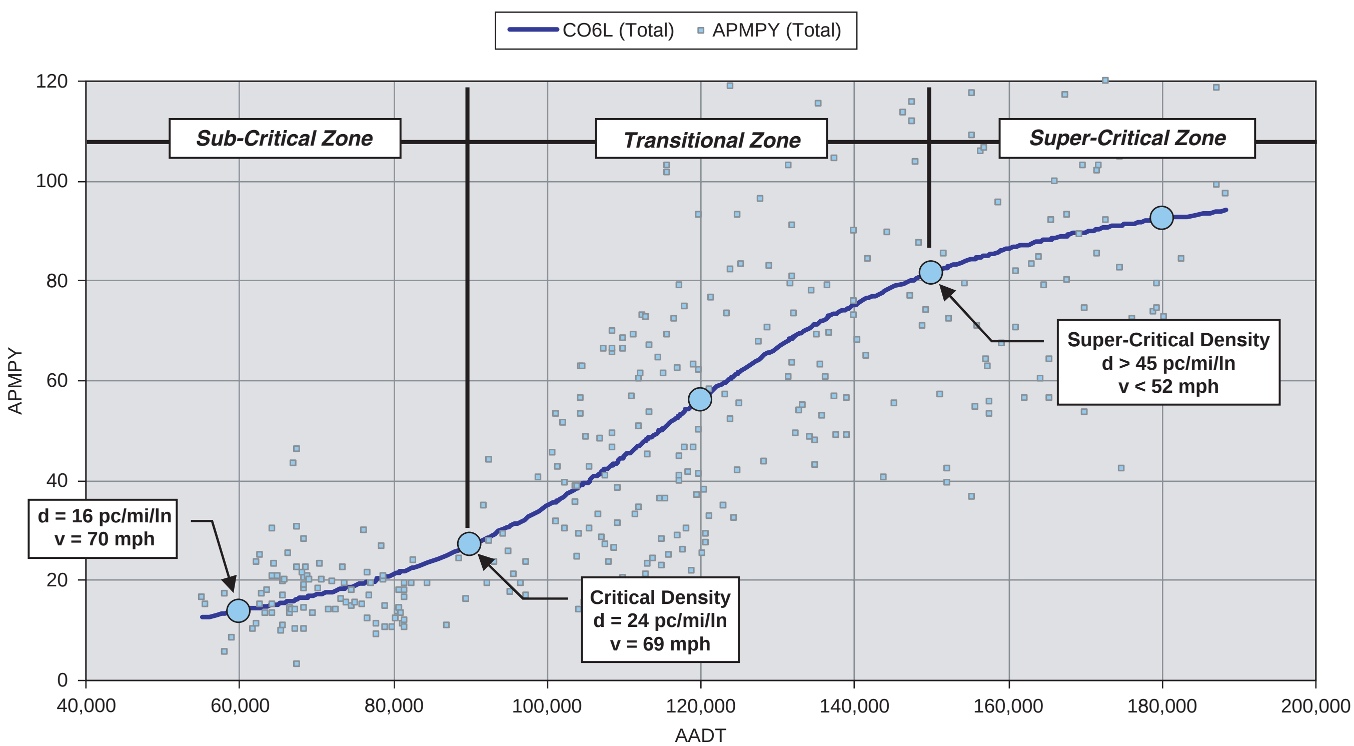


FIGURE 8 Six-lane freeway SPF: changes in traffic speed on density.

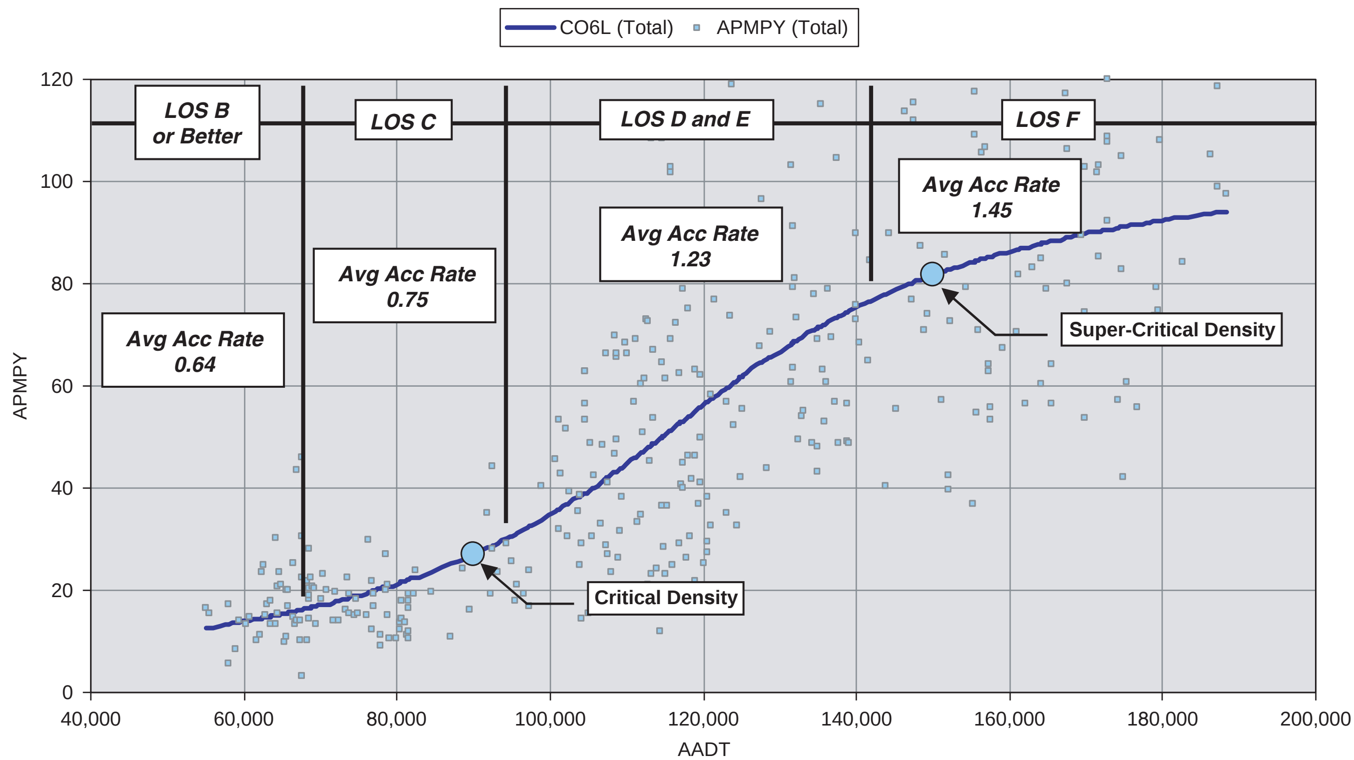


FIGURE 9 Six-lane total crashes SPF: changes in accident rates with LOS.

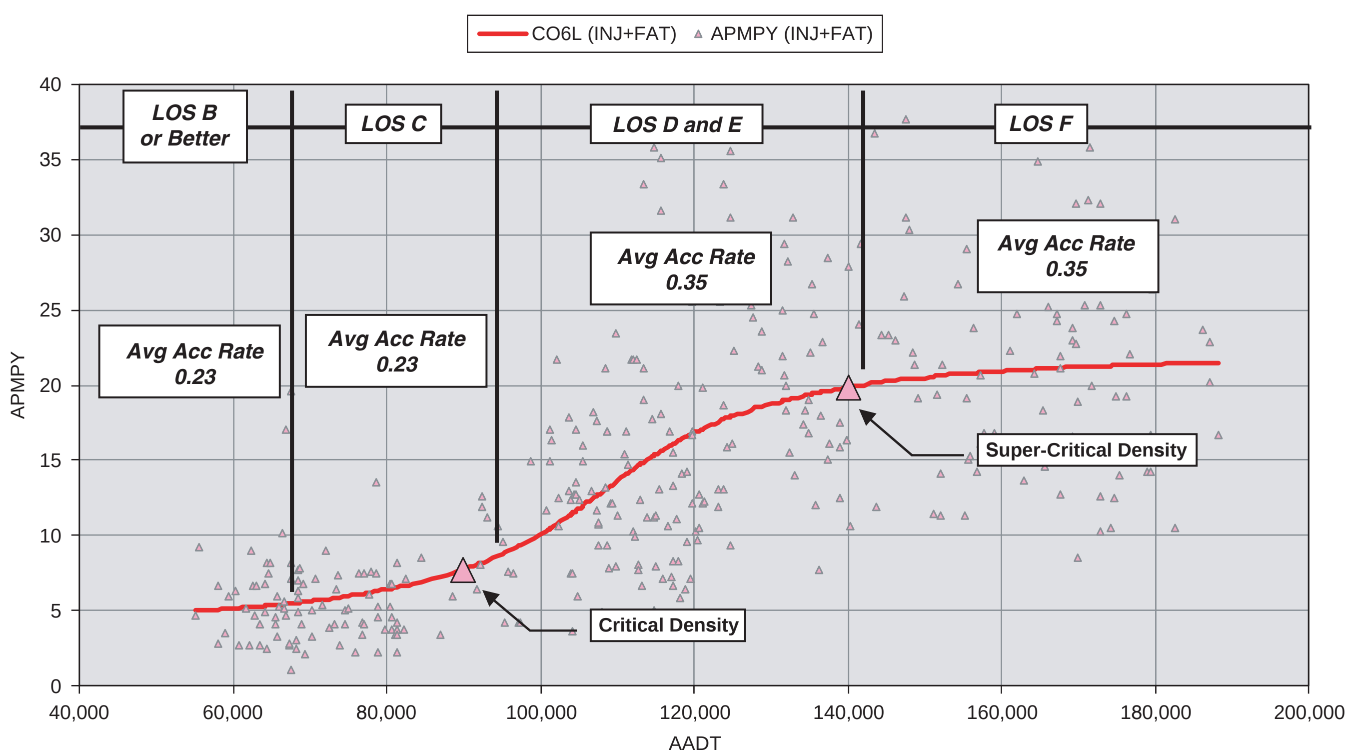


FIGURE 10 Six-lane injury and fatal crashes: changes in accident rates with LOS.

Garber (*16*) concluded that accident rates increase with an increase in the number of lanes.

What effect the number of lanes has on safety is a practical question. It was raised in the course of a major transportation study in the Denver metropolitan area in connection with a comparison of design alternatives from a safety standpoint. Here this question will be explored by a comparison of SPFs calibrated for multilane freeways with different numbers of lanes.

Comparison of Safety Performance Functions Using Derivatives

A dose–response curve or a sigmoid is made up of a central sloping section and two tail sections, the baseline and the maximum. The limits of a central sloping section of each SPF sigmoid were estimated by using a sliding interval analysis in the framework of the numerical differentiation technique described by Rao (*13*). The central sloping sections of SPFs with different numbers of lanes were compared and expressed as the distribution of their first derivatives.

The derivative of the function is the estimated slope of the tangent line to the curve at a point or the rate of change of the function at the point. The derivative of $\phi(u)$ can be easily calculated as follows:

$$\frac{d\varphi}{du} = \varphi(u)\left[1 - \varphi(u)\right]$$

Therefore, by the chain rule, the derivative of f with respect to x is

$$f'(x) = \beta_1 \varphi'(\mu + \gamma x)\gamma$$

The derivative of the SPF functions was estimated to allow quantitative comparison of the difference in the slopes of the curves at a range of AADT values. Figures 11 through 15 are a series of box plots that summarize the distribution of derivatives within the central section as a function of increasing number of lanes for each state. Examination of the distribution of derivatives for the smallest and largest number of lanes shows a general increase in the median and maximum derivatives. These results indicate that the slope of the SPF curves increases as the number of lanes increases.

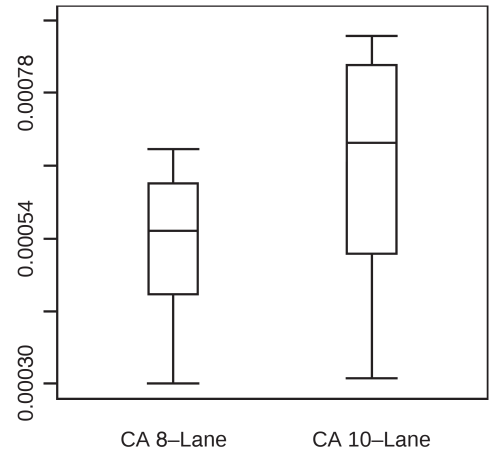


FIGURE 11 Box-plot comparison of derivatives, California SPF total: eight lanes (left) and 10 lanes (right).

To compare populations of derivatives within each state, nonparametric Mann–Whitney U-test (*17*) was performed. It is used to test whether populations have identical probability distribution functions. The Bonferroni (*18*) correction was used to adjust the p-value so as to account for the number of comparisons within each state. The pairwise test rejected the null hypothesis at all reasonable significance levels (p-values < .0001). The distributions of derivatives within each state for a given number of lanes were significantly different.

Accident rates change with AADT, and the slope of the SPF reflects how these changes take place. Any accident frequency derived from the SPF expressed in APMPY can be easily converted into accident rates measured in acc/MVMT. For instance, on the Colorado SPF calibrated for six-lane urban freeways, an AADT of 120,000 is expected to produce on average 56 APMPY, which can be directly converted to the accident rates as follows:

$$\frac{(56 \text{ acc/mile/year})\,1{,}000{,}000}{120{,}000 \text{ vpd}(1 \text{ mile})365 \text{ days/year}} = 1.28 \text{ acc/MVMT}$$

A comparison of average accident rates in the middle of the sigmoid SPFs (representing a similar degree of congestion during peak period

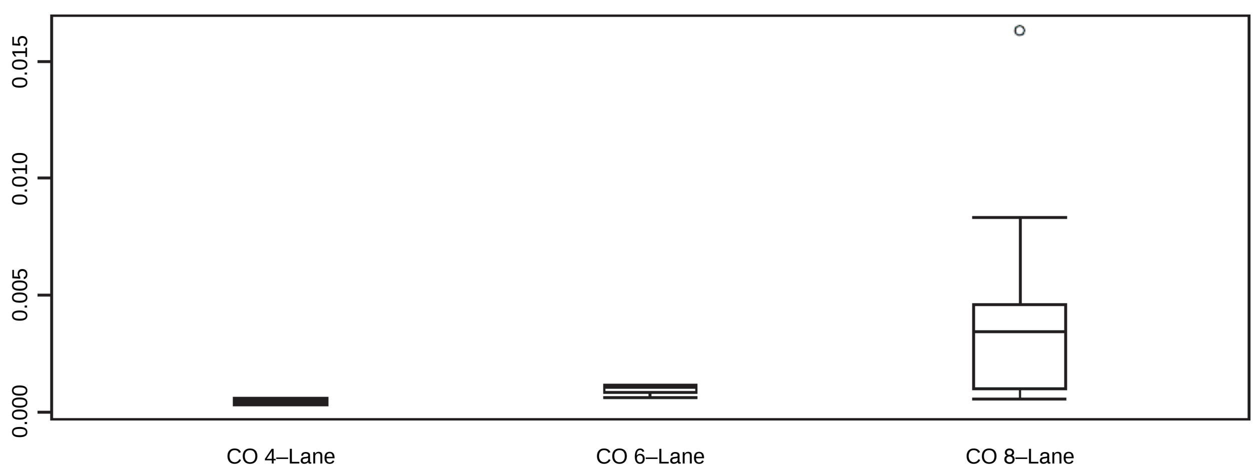


FIGURE 12 Box plots of derivatives, Colorado SPF total: four lanes (left), six lanes (center), and eight lanes (right).

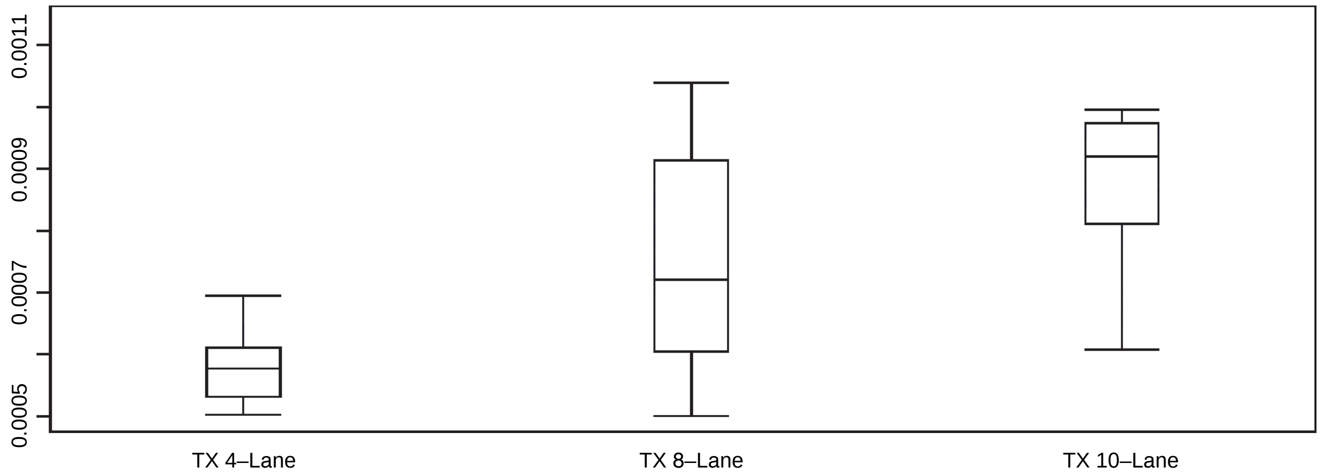


FIGURE 13 Box plots of derivatives, Texas SPF total: four lanes (left), eight lanes (center), and 10 lanes (right).

LOS-D) in Colorado showed a 25% increase in accident rates between four- and six-lane freeways and 40% between six- and eight-lane freeways.

Possible Explanation and Its Implications

An increase in the slope of the SPF associated with an increase in the number of lanes may possibly be explained by the increase in the number of potential opportunities for conflicts related to lane changes. According to the HCM (*9*), the number of lanes on a freeway segment influences free-flow speed. As the number of lanes increases, so does the opportunity for drivers to maneuver around slower traffic. Increased maneuverability tends to increase the average speed of traffic, but at the same time, it increases the speed differential as well as the number of crashes related to lane changes, such as sideswipes and rear ends. The number of possible conflicts in one direction is a function of the number of lanes on the freeway. An examination of the number of possible permutations of conflicts related to lane changes for each number of lanes identified the following combinatorial relationship:

For $n = 2$

$$C_n = f(n) = n(n-1)$$

For all $n > 2$

$$C_n = f(n) = n(n-1) + \frac{n!}{3!(n-3)!}$$

where C_n is the number of possible conflicts related to lane changes in one direction and n is the number of lanes in one direction.

A four-lane freeway with two lanes in one direction will have a potential for only two possible conflicts related to lane changes in each direction:

$$C_2 = f(2) = 2(2-1) = 2$$

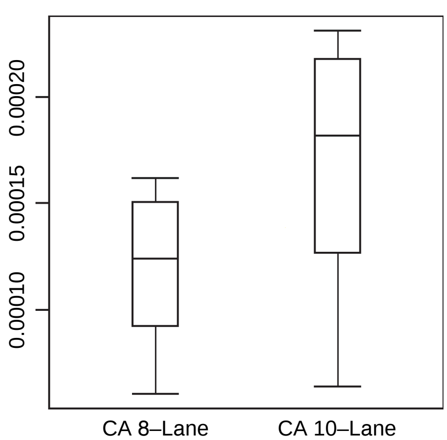


FIGURE 14 Box plots of derivatives, California SPF injury and fatal crashes: eight lanes (left) and 10 lanes (right).

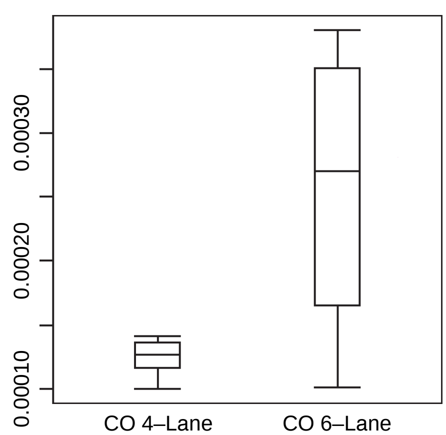


FIGURE 15 Box plots of derivatives, Colorado SPF injury and fatal crashes: four lanes (left) and six lanes (right).

A six-lane freeway with three lanes in one direction will have a potential for seven possible conflicts related to lane changes in each direction:

$$C_3 = f(3) = 3(3-1) + \frac{3!}{3!(3-3)!} = 7$$

An eight-lane freeway with four lanes in one direction will have a potential for 16 possible conflicts related to lane changes in each direction.

$$C_4 = f(4) = 4(4-1) + \frac{4!}{3!(4-3)!} = 16$$

Figure 16 is a graphical representation of the connection between the slope of the SPF and the number of possible conflicts related to lane changes. It approximates what will happen when the same road is widened from four to six to eight lanes with all other things being equal. Furthermore, it illustrates a direct relationship between the number of lanes and the number of possible conflicts related to lane changes. Clearly, not all conflicts have the same probability of occurrence; however, additional lanes increase the degree of freedom for things to go wrong.

Deterioration of safety associated with an increase in the number of lanes has the following important implication: the introduction of barrier-separated HOV lanes or managed lanes (including toll lanes) or the planning of dual–dual roadways may be more effective than widening of general-purpose lanes. During the design phase, however, it is critical to ensure that the interface between managed lanes and general-purpose lanes is carefully laid out to minimize turbulence related to merging and diverging.

Transition Between SPFs and Its Interpretation

The flat portion of the sigmoid (baseline) represents uncongested freeways. Freeways with more traffic are represented by a steep central portion, and heavily congested freeways are represented by another relatively flat portion (the maximum). It is reasonable to suppose that widening in the urban environment is generally triggered by a high degree of congestion, represented by a relatively flat portion of the sigmoid, the maximum. Once additional capacity is provided through widening, the traffic density is temporarily decreased.

This decrease in traffic density is associated with a more-forgiving driving environment reflected by the temporary safety improvement Δ (Figure 17). The figure shows that the same amount of traffic on $n + 2$ lanes in the overlap zone will generate fewer crashes than on n lanes at the same level of AADT. As development occurs in concert with rerouting of traffic from other routes, the critical density of traffic on the route with $n + 2$ lanes will be reached, and this route will then exhibit higher accident rates than observed on n lanes, manifested by the steeper slope of the SPF.

Impact of Crashes on Mobility

The HCM (*9*) predicts expected LOS on the basis of traffic demand and available capacity of the freeway without considering the adverse effect of incidents. A 10-lane freeway in California carrying an AADT of 300,000 is, on average, expected to experience 100 APMPY, which suggests that there is a virtual certainty that every 4-mi segment will experience at least one accident per day—most likely during peak periods. Queuing resulting from incidents on congested freeways is generally slow to dissipate and, given the expected frequency, represents more of a norm than an exception on busy multilane freeways. That slow dissipation may account for the fact that these freeways are congested most of the day and why expected speeds predicted by the HCM are more frequently found in the traffic analysis reports than in the field.

SUMMARY

Use of a neural network lends itself well to studying the systemic component of the relationship between safety and traffic exposure on multilane urban freeways. The functional shape of the SPF is well described by a sigmoid curve reflecting a dose–response type of relationship found in medicine and pharmacology, as well as other sciences. In all cases, accident data for urban freeways exhibited extra variation or overdispersion relative to the Poisson model.

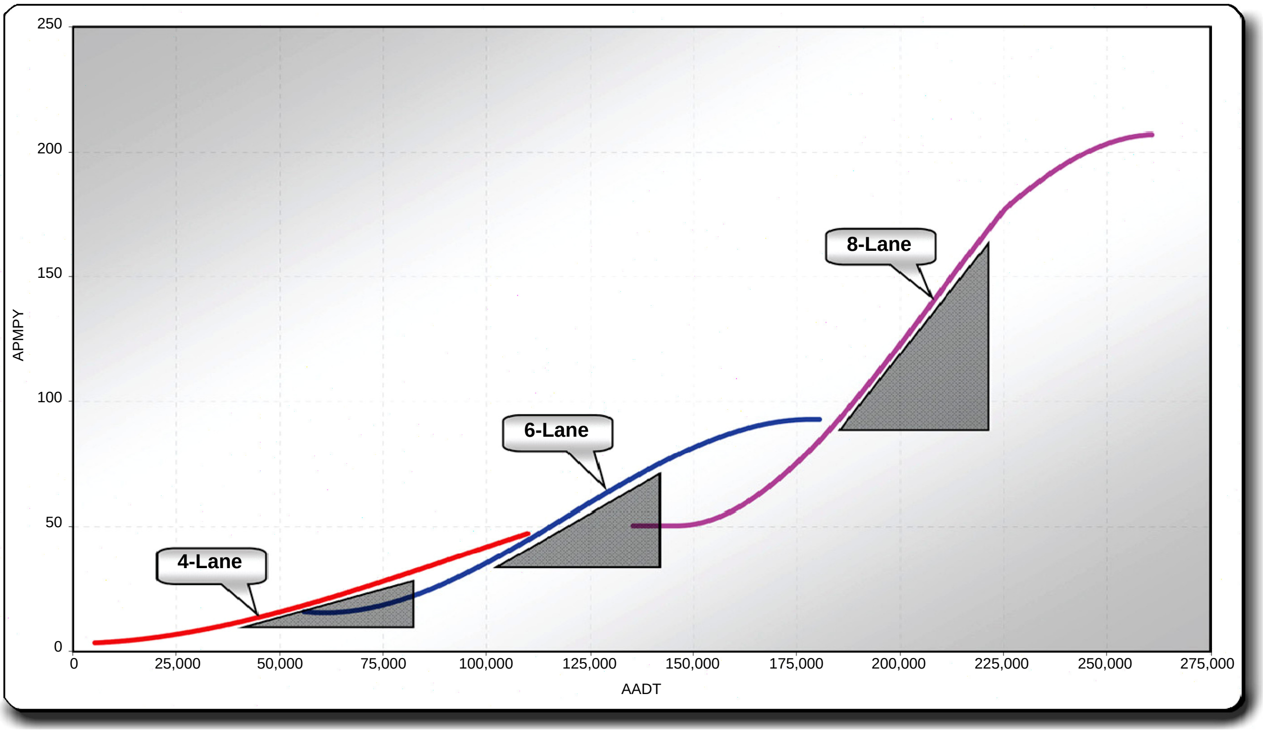
It was observed that on uncongested segments the number of crashes increases only moderately with increase in traffic; however, once some critical traffic density is reached, the number of crashes begins to increase at a much faster rate with an increase in traffic. This phenomenon is reflected by a steeper gradient of the SPF. A high density of traffic in the high range of AADT is associated with approaching supercritical density and a leveling off of the SPF, reflecting a high degree of congestion and a reduction in operating speeds.

Relating different LOS during peak periods with accident rates within SPF shows that total as well as injury and fatal crash rates increase with congestion. This observation suggests that peak spreading and congestion pricing have the potential for safety improvement in addition to more obvious mobility benefits. Understanding of the relationship between the LOS and the accident rate can be used to inform public policy, the transportation planning process, and highway design criteria. This understanding offers an important insight into the relationship between safety and mobility that will improve the quality of decisions made by practicing engineers, planners, and elected officials.

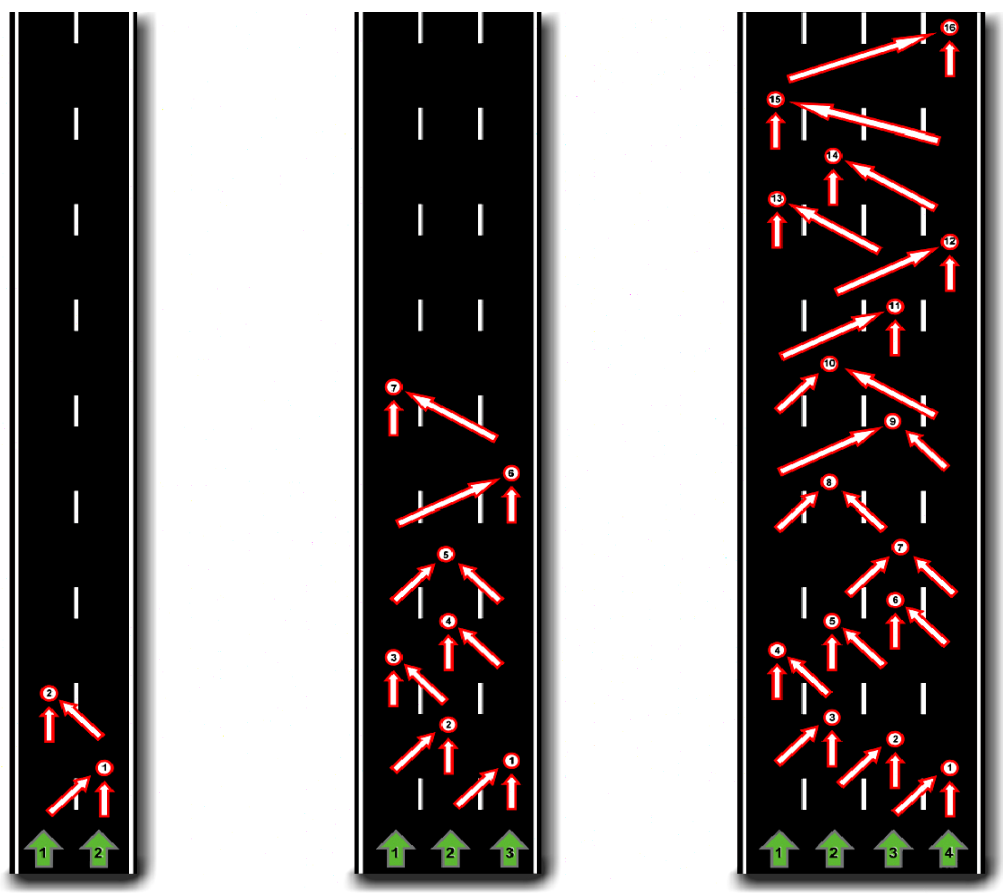
Comparison of slopes of SPFs for different numbers of lanes suggests that adding lanes on urban freeways initially results in safety improvement that diminishes as congestion increases. Once traffic demand goes up, the slope of the SPF, described by its first derivative, becomes steeper, and accidents increase at a faster rate with AADT than would be expected from a freeway with fewer lanes. This is found to be true for total as well as injury and fatal crashes.

While more research in this area is needed, this phenomenon may possibly be explained as follows: as the number of lanes increases, the opportunities for conflicts related to lane changes also go up. Furthermore, the increased maneuverability associated with the availability of more lanes tends to increase the average speed of traffic and the speed differential.

In addition to contributing to property damage and injuries, daily incidents on congested multilane freeways also adversely affect mobility. The introduction of barrier-separated HOV lanes, express lanes, and managed lanes (including toll or dual–dual roadways) are effective strategies to offset the increase of conflict opportunities associated with an increase in the number of lanes. During the design phase, however, it is critical to ensure that the interface between managed and general-purpose lanes is carefully laid out to minimize turbulence related to merging and diverging.



(a)



(b) (c) (d)

FIGURE 16 Number of lanes and number of conflicts related to lane changes: (*a*) comparison of total accidents by number of lanes on urban freeways, (*b*) conflicts for two-lane SPF, (*c*) conflicts on four-lane SPF, and (*d*) conflicts on eight-lane SPF.

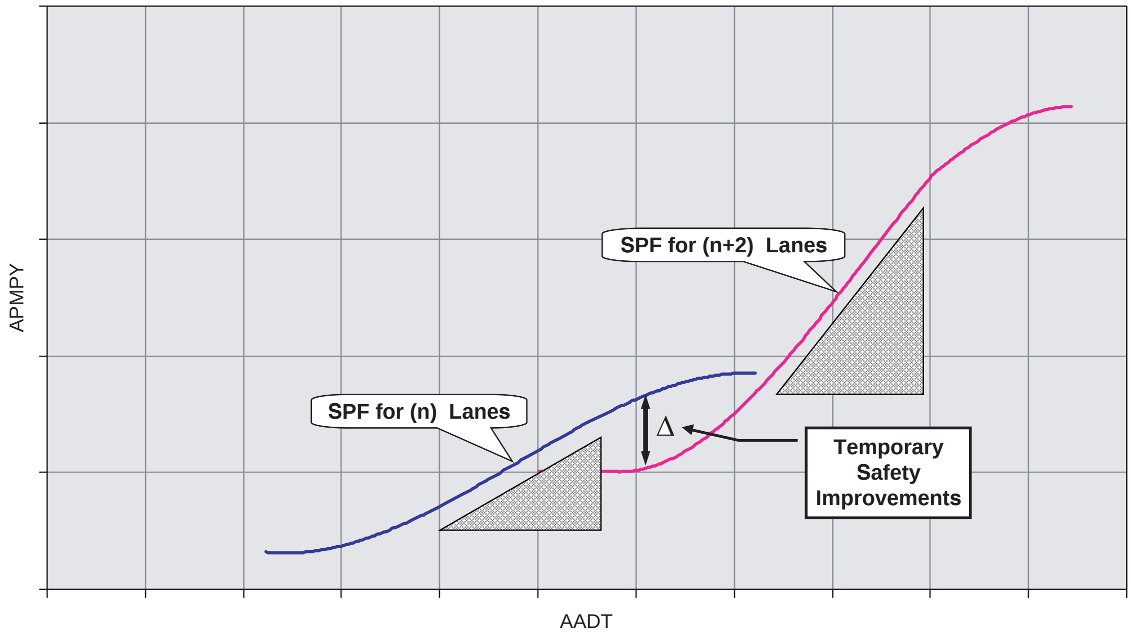


FIGURE 17 Transition between SPFs: comparison of total accidents by number of lanes on urban freeways.

Understanding of the relationship between the number of lanes and safety should be used to inform the public's involvement in the process of evaluating and selecting design alternatives. An increase in accident rates associated with an increase in the number of lanes can be viewed similarly to a negative side effect of a prescription medication and should be considered during the planning and design processes.

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