## Exploratory Analysis of Relationship between the Number of Lanes and Safety on Urban Freeways

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#### ABSTRACT

The relationship between freeway capacity and the number of lanes is reasonably well understood at present. In contrast to capacity, the relationship between the number of lanes and safety is not fully understood or systematically considered when planning capacity improvements.

During the planning and design phase the discussion is centered on the degree to which design alternatives comply with geometric design standards and what Level of Service (LOS) is provided. It is generally believed by the practitioners that additional capacity afforded by additional lanes is associated with more safety. How much safety and for what time period is generally not considered. Exploratory analysis of the Safety Performance Functions (SPF) for multilane freeways in Colorado. California and Texas suggests that adding lanes may initially result in a temporary safety improvement that disappears as congestion increases. As Annual Average Daily Traffic (AADT) 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. This may possibly be explained by the fact that increase in the number of lanes is associated with increase in the number of potential lane-change-related conflict opportunities. Understanding of the relationship between number of lanes and safety should be used to inform the public involvement process in evaluating and selecting design alternatives. Additionally, high AADT on multilane freeways is associated with high crash frequency and consequently reduced mobility.

#### Introduction

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

We know from the Highway Capacity Manual (1) that capacity is increased proportionally with the number of lanes with some adjustment for 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 at present.

Research conducted by Council and Stewart (2) on the safety effects of converting two-lane roads to four lanes finds 40% to 60% reduction in crashes as a result of conversion to 4-lane cross-section.

Milton and Mannering (3) found that increasing the number of lanes in rural Washington State leads to more accidents.

Noland and Oh (4) 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 (5) observed that crash rates increase with number of lanes on urban roadway sections.

Garber (6) concluded that accidents rates increase with 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 Metro area in connection with comparing design alternatives from a safety standpoint. We will explore this question by comparing Safety Performance Functions (SPF) calibrated for multilane freeways with different numbers of lanes.

Safety Performance Functions 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/mile per year). Much substantive and comprehensive work in the area of accident modeling was undertaken by Hauer and Persaud (7), Hauer (8) and Lord, Washington and Ivan (9) and Abdel-Aty and Radwan (5). Details concerning dataset preparation and model fitting for the development of the Safety Performance Functions were described by Kononov and Allery (10).

#### DATASET PREPARATION AND MODEL DEVELOPMENT

Five years of accident data from Colorado, California and Texas was used to develop Safety Performance Functions (SPF) for the selected multilane urban freeways. California data were obtained from the Highway Safety Information System (HSIS), Colorado and Texas datasets were provided by their Departments of Transportation. All of the accidents that occurred on ramps and crossroads were removed prior to fitting of 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 injury and fatal only crashes. Due to data availability only total accidents SPF models were calibrated for Texas.

SPFs were developed using Neural Networks, a subset of a general class of nonlinear models. We used Neural Networks to analyze the data which consists of observed, univariate responses  $Y_i$  known to be dependent on a corresponding one-dimensional input  $x_i$ . Neural Networks are not constrained by a pre-selected functional form and specific distributional assumptions. For our application,  $Y_i$  = Accidents Per Mile Per Year (APMPY) and  $x_i$  = Annual Average Daily Traffic (AADT).

The model becomes:

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

where

 $f(x_i, \theta)$  = the nonlinear function relating  $Y_i$  to the independent variable  $x_i$  for the *ith* observational unit,

 $\theta$  = a *p*-dimensional vector of unknown parameters, and

 $e_i$  = is a 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

 $\varphi(u) = e^{u} / (1 + e^{u})$ - a logistic distribution function  $\beta_{k}$  = are known as connection weights and  $\beta_{0}, \beta_{1}, \gamma_{1}, u_{1}$  = the parameters to be estimated  $\mu_{k}$  = the biases, Ripley (11). *K* = the 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 parameters  $\beta_0, \beta_1, \gamma_1, u_1$  for each dataset 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. We have chosen *K*=1 based on general understanding of the underlying physical phenomenon. Additionally the complexity of the model is most often chosen based on the generalized crossvalidation (GCV) model-selection criterion. Cross-validation is a standard approach for selecting smoothing parameters in nonparametric regression described by Wahba (12). **Figures 1** through **3** represent SPFs and model fit information for the selected multilane freeways in Colorado, California and Texas. The R<sup>2</sup> parameter, predicted values from the model versus the residuals and the root mean squared error (RMSE) 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 satisfactory.



Figure 1 Colorado 6-Lane SPF Total and Model Fit Parameters



Figure 2 California 8-Lane Freeway SPF Total and Model Fit Parameters



Figure 3 Texas 8-Lane Freeway SPF Total and Model Fit Parameters

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 Safety Performance Functions 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 other sciences. In all cases, accident data for urban freeways exhibited extra-variation or over-dispersion relative to the Poisson model.

## 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). We compared SPFs with different numbers of lanes by comparing their central sloping sections expressed by 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  $\varphi(u)$  can be easily calculated as follows:

$$\frac{d\varphi}{du} = \varphi(u)(1-\varphi(u))$$

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

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

We estimated the derivative of the SPF functions to quantitatively compare the difference in the slopes of the curves at a range of AADT values. **Figures 4 through 8** are a series of box-plots summarizing the distribution of derivatives within the central section as a function of increasing number of lanes, for each state. Examining the distribution of derivatives for the smallest and largest number of lanes, there is a general increase in the median and maximum derivatives. This indicates that the slope of the SPF curves increases as the number of lanes increases.

To compare populations of derivatives within each state we performed the *nonparametric Mann-Whitney U test (14)*. It is used to test whether populations have identical probability distribution functions. We applied the Bonferroni (15) correction to adjust the p-value in order to account for the number of comparisons within each state. *The pairwise test rejected the null hypothesis at all reasonable significance levels (p-values < 0.0001)*. The distributions of derivatives within each state for a given number of lanes is significantly different.



Figure 4 Box-Plots Comparison of Derivatives California SPF Total



Figure 5 Box-Plots of Derivatives Colorado SPF Total







#### Figure 8 Box-Plots of Derivatives Colorado SPF Injuries and Fatal Crashes

Accident rates change with AADT, and slope of SPF reflects how these changes take place. Any accident frequency derived from the SPF expressed in accidents per mile per year (APMPY) can be easily converted into accident rates measured in accidents per million vehicle miles traveled (acc. per mvmt). For instance, on the Colorado SPF calibrated for 6-lane urban freeways the AADT 120,000 is expected to produce on the average 56 accidents per mile per year, 56 acc/mi annually can be directly converted to the accident rates as follows:

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

When we compared average accident rates in the middle of the sigmoid SPFs (representing similar degree of congestion during peak period LOS-D) in Colorado, we observed 25% increase in accident rate between 4- and 6-lane freeways and 40% between 6- and 8-lane freeways.

#### Possible Explanation

Increase in the slope of SPF associated with increase in the number of lanes may possibly be explained by the increase in the number of potential lanechange-related conflict opportunities. According to the Highway Capacity Manual (HCM)(1), the number of lanes on a freeway segment influences Free Flow Speed (FFS). As the number of lanes increases, so does the opportunity for drivers to maneuver around slower traffic. Increased maneuverability tends to increase average speed of traffic, but at the same time it increases speed differential as well as the number of lane-change-related crashes 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. We have examined the number of possible permutations of lane-change-related conflicts for each number of lanes and identified the following generic relationship:

$$C_n = f(n) = n(n-1) + (n-2)^2$$

 $C_n$  - Number of possible lane-change-related conflicts in one direction

*n* - Number of lanes in one direction

A 4-lane freeway with 2 lanes in one direction will have a potential for only 2 possible lane-change-related conflicts in each direction.

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

A 6-lane freeway with 3 lanes in one direction will have a potential for 7 possible lane-change-related conflicts in each direction.

$$C_3 = f(3) = 3(3-1) + (3-2)^2 = 7$$

An 8-lane freeway with 4 lanes in one direction will have a potential for 16 possible lane-change-related conflicts in each direction.

$$C_4 = f(4) = 4(4-1) + (4-2)^2 = 16$$

**Figure 9** is a graphical representation of the connection between the slope of SPF and the number of possible lane-change-related conflicts. Additionally it illustrates a direct relationship between the number of lanes and the number of possible lane-change-related conflicts. Clearly not all conflicts have the same probability of occurrence; however, additional lanes increase the degree of freedom for things to go wrong.



Number of Lane-Change-Related Conflicts for 4, 6, and 8 Lanes SPF

### Transition between SPFs and Its Interpretation

SPF modeling applying Neural Networks to datasets from Colorado, California and Texas suggests that the functional shape of the Safety Performance Function is well described by a sigmoid curve reflecting a dose-response-like relationship found in medicine and pharmacology, as well as other sciences. It may possibly be explained as follows:

The flat portion of the sigmoid (baseline) represents un-congested freeways where crashes increase 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 increase in traffic. Freeways with traffic density greater than critical during peak period are represented by a steep central portion of the sigmoid; however, further examination of the SPF suggests that on segments with high AADT (LOS-F during peak period), the function begins to level off, reflecting decrease in accident rates related to a high degree of congestion and significant reduction in operating speeds. These freeways are represented by another relatively flat portion (the maximum) of the sigmoid.

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.



- Figure 10

This decrease in traffic density is associated with a more forgiving driving environment reflected by the temporary safety improvement  $\Delta$ . Figure 10 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 it 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 Highway Capacity Manual (HCM) (1) predicts expected LOS based on 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 acc/mile per year, which suggests that there is a virtual certainty that every 4-mile segment will experience at least 1 accident per day and 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 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.

## Application

Understanding the relationship between the number of lanes and safety is of particular interest to a number of Departments of Transportation (DOT) around the country considering design and construction of the managed lanes. Managed lanes are separated from the general purpose lanes by a barrier or a buffer. They carry High Occupancy Vehicles (HOV), buses and Single Occupancy Vehicles (SOV) paying toll via transponders. These managed lanes are often referred to as HOT (High Occupancy Toll) lanes. A recent study by the Texas Transportation Institute (TTI) (16) suggests that barrier-separated facilities are safer than those separated by a buffer. *In the climate of limited financial resources available for transportation construction of additional managed or toll lanes often are the only way for the DOTs to provide additional mobility on highly congested urban freeway corridors.* The following example illustrates how understanding of the relationship between number of lanes and safety can inform the public involvement process of evaluating and selecting design alternatives.

Existing 6-lane urban Interstate Freeway X is highly congested, two possible widening alternatives to 10 lanes are being considered. Alternative A, **Figure 11**, consists of 5 General Purpose (GP) lanes in one direction, and Alternative B, **Figure 12**, is a 5-lane section in one direction comprised of 2 managed lanes (HOV/HOT) barrier-separated from 3 GP lanes.



$$n = 5$$
  
Cn = f(n) = n(n-1) + (n-2)<sup>2</sup> = 5(5-1) + (5-2)<sup>2</sup> = 29



Figure 12 Alternative B - (2) HOT Lanes + (3) GP Lanes

The number of possible lane-change-related conflicts for Alternative B can be computed as follows:

$$n_{1} = 2 \text{ and } n_{2} = 3$$

$$C_{n1} + C_{n2} = f(n_{1}) + f(n_{2}) = n_{1}(n_{1} - 1) + (n_{1} - 2)^{2} + n_{2}(n_{2} - 1) + (n_{2} - 2)^{2} = 2(2 - 1) + (2 - 2)^{2} + 3(3 - 1) + (3 - 2)^{2} = 9$$

There are more than 3 times as many lane change conflict opportunities associated with Alternative A than with Alternative B, albeit not all conflicts have the same probability of occurrence. Alternative B, however, will require slightly more right of way to accommodate concrete barrier and a shoulder. Additionally during planning and design phase it is critical to ensure that interface between managed lanes and general purpose lanes is carefully laid out to minimize turbulence related to merging and diverging. Additional access points required to

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get in and out of the managed lanes are naturally associated with additional crashes. Their adverse impact, however, will be offset by reducing the number of potential lane change conflict opportunities from 29 for the Alternative A down to only 9 for the Alternative B.

## SUMMARY

Comparison of slopes of Safety Performance Functions 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 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 lane-change-related conflicts also go up. As the number of lanes increases from 2 to 5 in one direction, the number of potential lane-change-related conflict opportunities increases from 2 to 29. Additionally, increased maneuverability associated with availability of more lanes tends to increase average speed of traffic and speed differential.

In addition to contributing to property damage and injuries, daily incidents on congested multilane freeways also adversely impact mobility. 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 increase in the number of lanes. During design phase, however, it is critical to ensure that interface between managed and general purpose lanes is carefully laid out to minimize turbulence related to merging and diverging.

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

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