# Relationship between Freeway Flow Parameters and Safety and Its Implication on Adding Lanes

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## ABSTRACT

Decisions to add lanes on a freeway are motivated by the need to relieve congestion. It is generally believed by practicing engineers and planners that decreased congestion resulting from adding lanes is associated with some degree of improved safety, yet the majority opinion among researchers is that accident rates increase with increase in the number of lanes. Despite of over 70 years of modern road building these conflicting views have not been reconciled. This paper first examines the relationship of traffic flow parameters such as volume, density, and speed to safety by calibrating corridor specific safety performance functions. On the basis of understanding this relationship a possible explanation of the effect of adding lanes on safety is formulated. Empirical examination of the relationship of flow, density, and speed to the crash rate on selected freeways in Colorado suggests that, as flow increases crash rate initially remains constant until a certain critical threshold combination of speed and density is reached. Once this threshold is exceeded, the crash rate rapidly rises. The rise in crash rate may possibly be explained by the fact that increase in density without notable reduction in speed produces headways so small that it becomes very difficult or impossible to compensate for driver's error. This model suggests that following construction of additional lanes crash rates initially decline because of lower traffic volume/density per lane. However, as development and rerouting occurs, freeways with more lanes are expected to have higher crash rates due to more opportunities for lane change related conflicts.

*"Simpler explanations are, other things being equal, generally better than more complex ones"*

*Occam's Razor Principle*

## INTRODUCTION

### *Relating Freeway Flow Parameters to Safety*

Relationships of speed to flow and density to flow for a typical basic freeway segment are well understood at present and are documented by the successive editions of the Highway Capacity Manual (HCM)(1). All recent freeway studies show that speed on freeways is insensitive to flow in the low to mid range. Increase in flow and density without notable reduction in speed has a significant influence on safety. This influence, however, has not been studied extensively and has attracted only limited interest from researchers to date. Lord et al. (2) observed that most research has focused on determining the relationship between crashes and annual average daily traffic (AADT), while little attention has been focused on the relationships of vehicle density, level of service (LOS), vehicle occupancy, volume to capacity (V/C) ratio and speed distribution. Zhou and Sisiopiku (3) found that crash rates typically follow a U-shaped relationship when plotted as a function of V/C ratio. Traditional safety performance functions relate accident occurrence to annual average daily traffic (AADT). Persaud and Dzbik (4) observed that a difficulty with this approach is that a freeway with intense flow during rush periods would clearly have a different accident potential than a freeway with the same AADT but with flow evenly spread out throughout the day. Kononov et al. (5) observed that on uncongested freeways the number of crashes increases 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. Garber and Subramanyan (6) related crashes to lane occupancy and concluded that peak crash rates do not occur during peak flows. Harwood in (7) noted that it would be extremely valuable to know how safety varies with Volume/Capacity (V/C) ratio and what V/C ratios provide the minimum accident rate. Hall and Pendelton (8) observed that knowledge of the definite relationship between V/C ratio and crash rate would help engineers and planners asses safety implications of highway improvements designed to increase capacity. In (2) Lord et al. conclude that "despite overall progress, there is still no clear understanding about the effects of different traffic flow characteristics on safety."

Figure 1 (EXHIBIT 23-3) from the 2000 Edition of the Highway Capacity Manual (HCM) (1) shows the speed-volume/density relationship and Level of Service (LOS) for basic freeway segments. It reflects the fact that drivers on modern freeways are slowing down very little or not at all as LOS deteriorates from A to D. Considering that perception-reaction time and vehicle characteristics remain unchanged while there are considerably more vehicles in the same space traveling at substantially the same speed as before, an increased probability of crash occurrence is highly plausible. This increase would be reflected by changes in the crash rate. For instance, a freeway with free-flow speed of 70 mph at point 1 carrying 600 pc/h/ln ($V_1$) has density $d_1$ = 8.6 pc/mi/ln and operates at LOS A. When congestion builds up to 1750 pc/hr/ln ($V_2$) (boundary between LOS-C and LOS-D.) the resulting density rises to $d_2$ = 26 pc/mi/ln and operating speed drops only slightly to 68 mph.

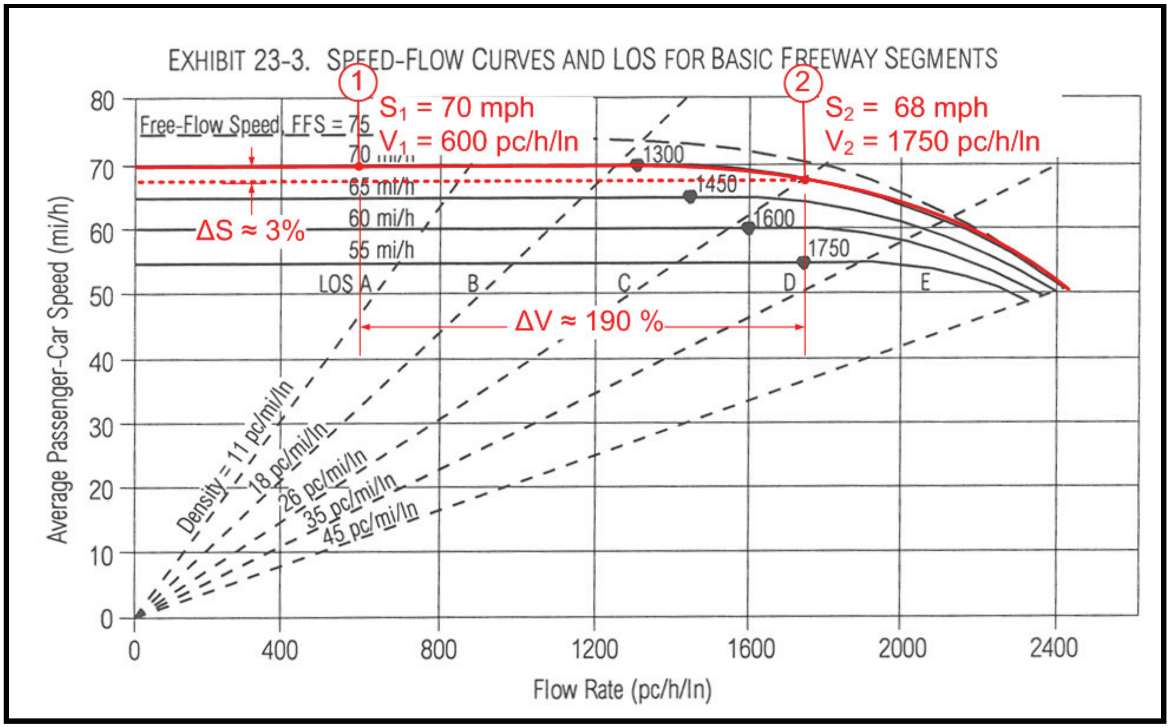


**Figure 1 Speed-Flow Curves and LOS**

As a transition is made from point 1 to point 2, we observe densities that are almost 3 times greater and a decrease in speed of only 3%. When these flow parameters are examined for a freeway with Free-Flow Speed of 55 mph we observe that volume rises from 600 vph (density =10.9 pc/mi/ln) to 1,750 vph (density=31.8 pc/mi/ln) without any speed reduction. Compression of flow without corresponding reduction in speed is likely to have an adverse effect on safety; calibration of this effect is explored in this paper

### *Relating Number of Lanes to Safety*

Decisions to add travel lanes on a freeway are motivated by the need to relieve congestion. It is generally believed by practicing engineers and planners that decreased congestion resulting from adding lanes 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. These two conflicting views on this very fundamental issue have not been reconciled despite over 70 years of modern road building.

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 (13) 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 (14) found that increasing the number of lanes in rural Washington State leads 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 increase with number of lanes on urban roadway sections.

Kononov et al. (5) showed that adding lanes on urban freeways leads to increase in the crash rate by comparing slopes of safety performance functions described by their first derivatives.

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

This paper first examines the relationship of traffic flow parameters such as volume, density, and speed to safety by calibrating corridor specific safety performance functions based on hourly volume. On the basis of understanding this relationship a possible explanation of the effect of adding lanes on safety is formulated.

## MODEL DEVELOPMENT

### *Dataset Preparation*

Hourly volume, operating speed and free-flow speed data were collected from existing automatic traffic recording (ATR) stations around the Denver metropolitan area 4-lane freeways and a segment of Interstate 70 (I-70), which carries ski resort traffic in mountainous terrain. Mainline crash history was obtained from the CDOT crash database for every hour over a five (5) year period for every freeway in the dataset. All crashes that occurred on ramps and cross roads were removed prior to fitting the models.

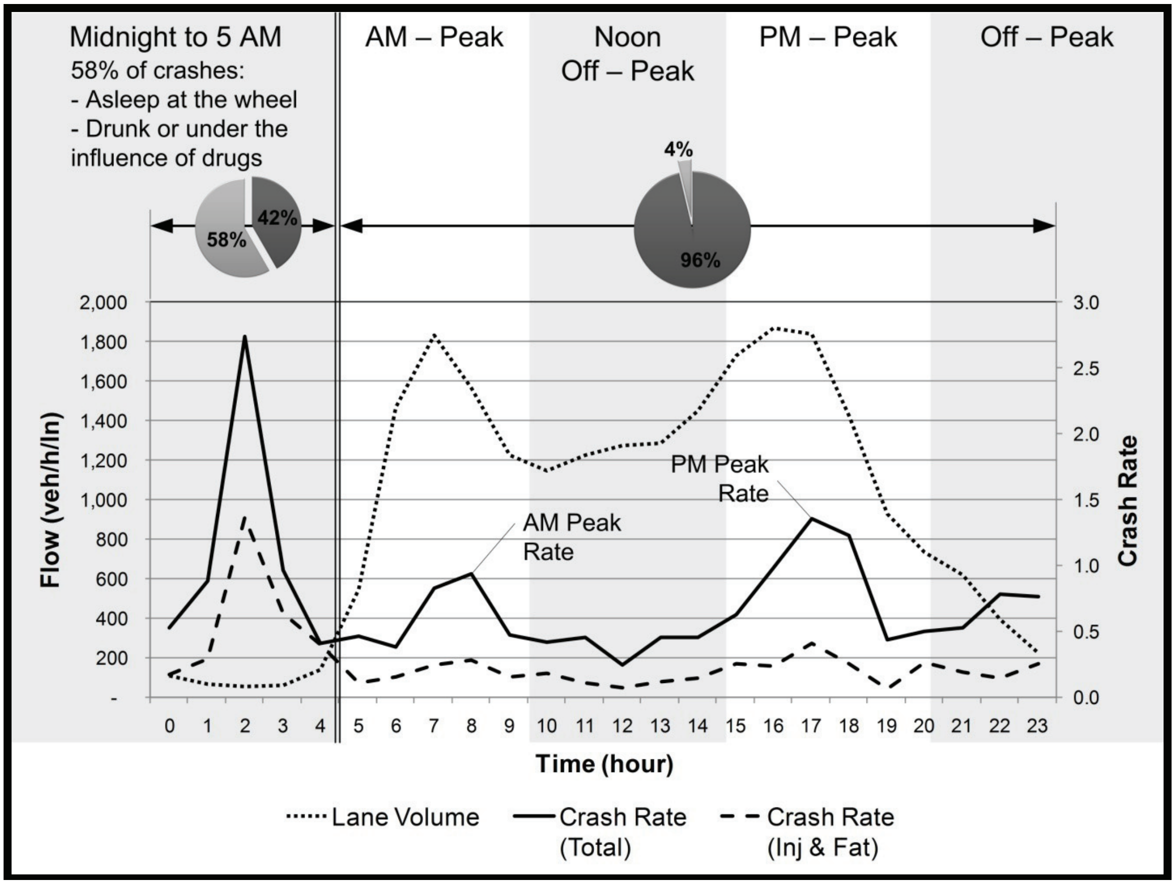


**Figure 2 Changes in Volume and Crash Rate over the 24 hr Period on Denver Area Urban Freeways**

Matching hourly volume on every segment with its crash history enabled us to compute crash rate in accidents per million mile traveled (acc/mvmt) for every hour of the 24 hour period for all freeways in the dataset. A composite graph representing several Denver area 4-lane freeways demonstrating changes in volume and crash rates throughout the day is presented in Figure 2.

It is of interest to note that between the hours of midnight and 5 AM nearly 60% of all crashes involved alcohol or drug use or falling asleep at the wheel as compared with only 4% the rest of the day. Such a dramatic difference in driver performance abilities and crash causality suggests a qualitatively different phenomenon. A mix of impaired and fatigued drivers with low volumes produces very high crash rates when compared with day time safety performance of the same segments. It may possibly explain the U-shaped relationship identified by Zhou and Sisiopiku in (3). The impaired driver issue, a largely behavioral problem, is distinct from issues near or at peak times. Recognizing this, a portion of the dataset containing safety performance data between midnight and 5 AM was removed prior to calibration of the corridor specific Safety Performance Functions. Additionally Figure 2 suggests that the afternoon peak is characterized by slightly higher crash rates than the morning peak. It may possibly be speculated that commuters are more fatigued, more eager to get home from work, and less focused on the driving task. Also, the higher crash rates may possibly be attributed to more secondary crashes resulting from the longer duration of the PM peak period. With this in mind, we have calibrated separate corridor specific Safety Performance Functions (SPF) containing morning and afternoon peak periods on urban freeways and a seasonal safety performance function for I-70 carrying ski resort traffic.

### *Neural Networks*

Corridor specific SPFs relating freeway flow parameters with crash rate were developed using Neural Networks, a subset of the 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 corresponding one-dimensional inputs $x_i$. Neural Networks are not constrained by a pre-selected functional form and specific distributional assumptions. For our application, $Y_i$ = Crash Rate (acc/mvmt) and $x_i$ = V, where V is hourly volume per lane (pc/h/pl). 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 function,
$\beta_0, \beta_k, \gamma_k, \mu_k$ = the parameters to be estimated for $i = 1,...K$ , and
$K$ = the number of hidden units.

The $\beta_k$'s are known as connection weights and the $\mu_k$ are the biases , Ripley (9).

The function $f$ is a very flexible nonlinear model used in this application to capture the overall shape of the observed data. 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 result is still a very flexible nonlinear model.

The parameters $\beta_0, \beta_1, \gamma_1, \mu_1$ 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 cross validation (GCV) model-selection criterion. Cross-validation is a standard approach for selecting smoothing parameters in nonparametric regression described by Wahba (10). Overall model fit to the data is quite good (Figures 3-6).

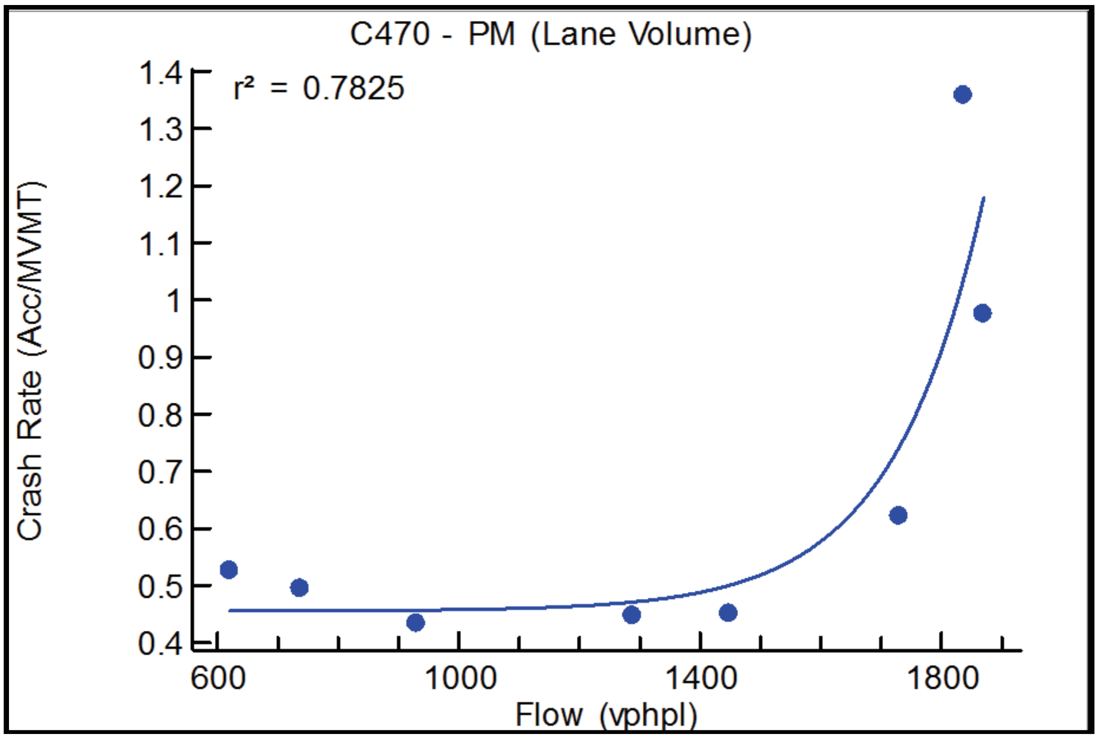


**Figure 3 Corridor-Specific SPF C-470 (PM) (4 lanes, 7 miles)**

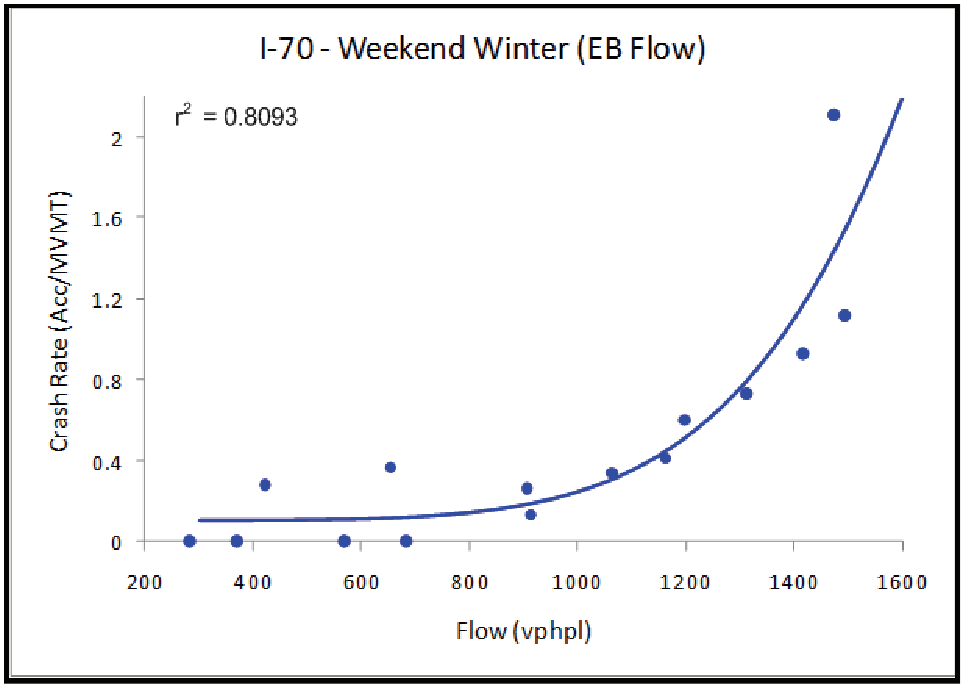


**Figure 4 Corridor-Specific SPF I-70 Weekend Winter (EB Flow) (4 lanes, 5 miles)**

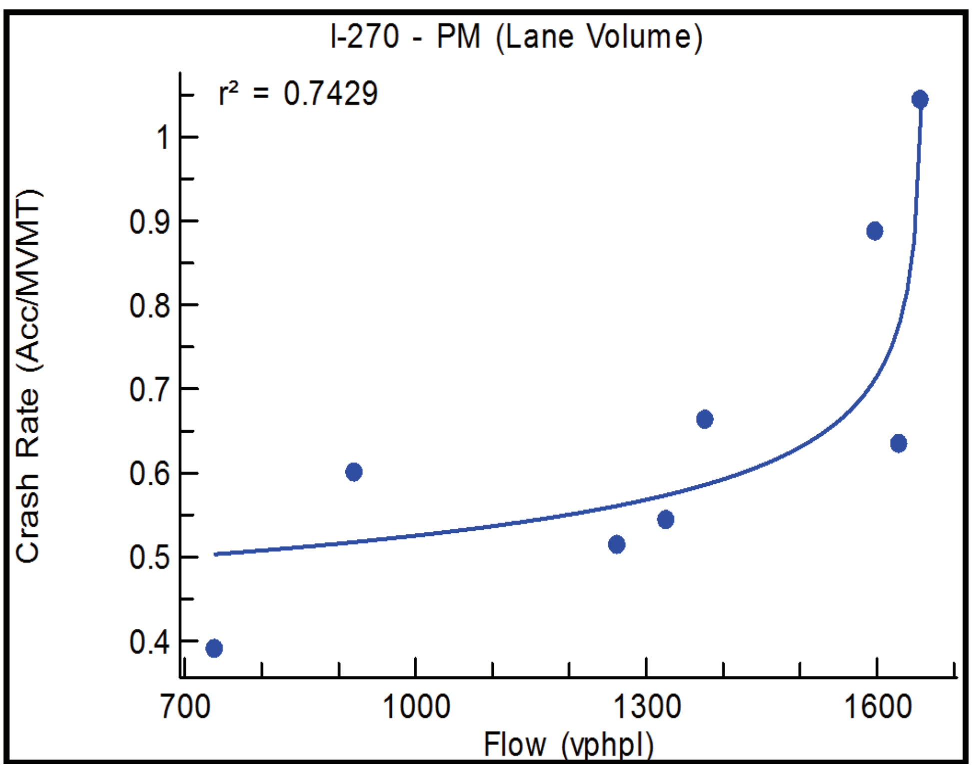


**Figure 5 Corridor-Specific SPF I-270 (PM) (4 lanes, 5 miles)**

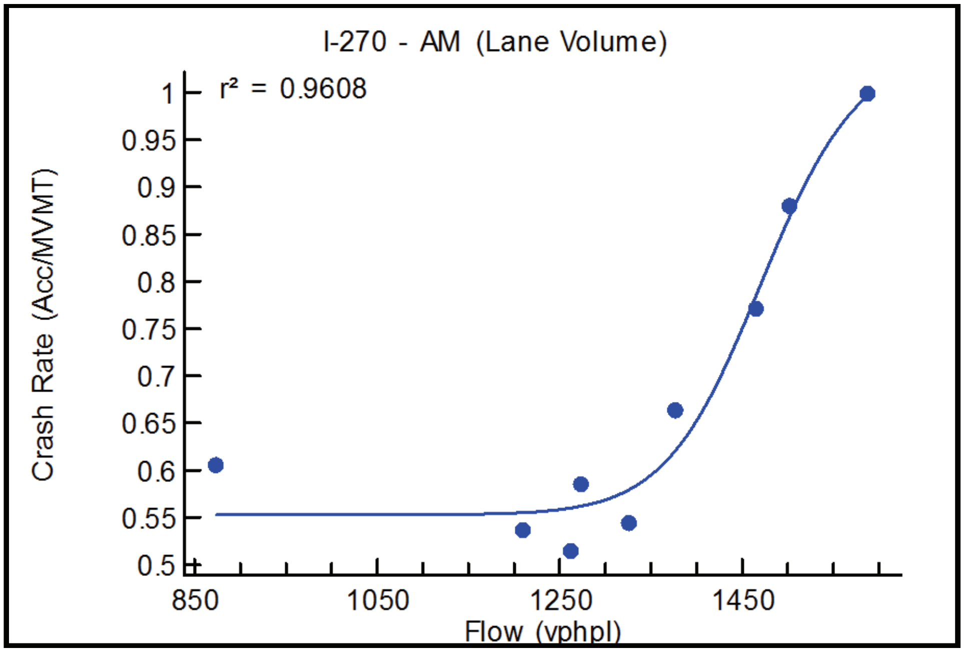


**Figure 6 Corridor-Specific SPF I-270 (AM) (4 lanes, 5 miles)**

Recognizing that volume V is a product of traffic density (d) times speed (s) enables us to consider density in concert with speed as we examine the relationship between flow characteristics and safety. Figures 3-6 reflect these relationships for several four lane freeways in the Denver metro area and a heavily traveled rural freeway in a mountainous environment. It is important to note that the inventory of freeways used in this paper did not include any freeways which exceed volumes of 1,900 vphpl. This may explain why the reduction in crash rates associated with heavy congestion described by Kononov (5) is not reflected in the functional form of corridor specific SPFs in this study. Further, the limited range of speeds represented prevents detailed analysis of the way in which speed enters into the equation. Figures 3-6 suggest that total crash rate remains relatively stable until a certain threshold value of V is reached. Once it is exceeded, however, the crash rate begins to rise rapidly. The relationship between V=ds and crash rates seems to resemble a phase change phenomenon in chemistry or critical mass in physics. A possible explanation may be that if V(ds) exceeds a certain critical threshold value $V_c$ available headway becomes too small for the prevailing speed to allow drivers to react effectively to changing traffic conditions. Furthermore two (2) distinct operational regimes can be observed on Figure 7, as well all other corridor specific SPFs. Regime-1 where $V<V_c$ and Regime-2 where $V>V_c$. The critical value of $V_c$ can be estimated using *a* sliding interval analysis in the framework of the numerical differentiation technique described by Rao (15).

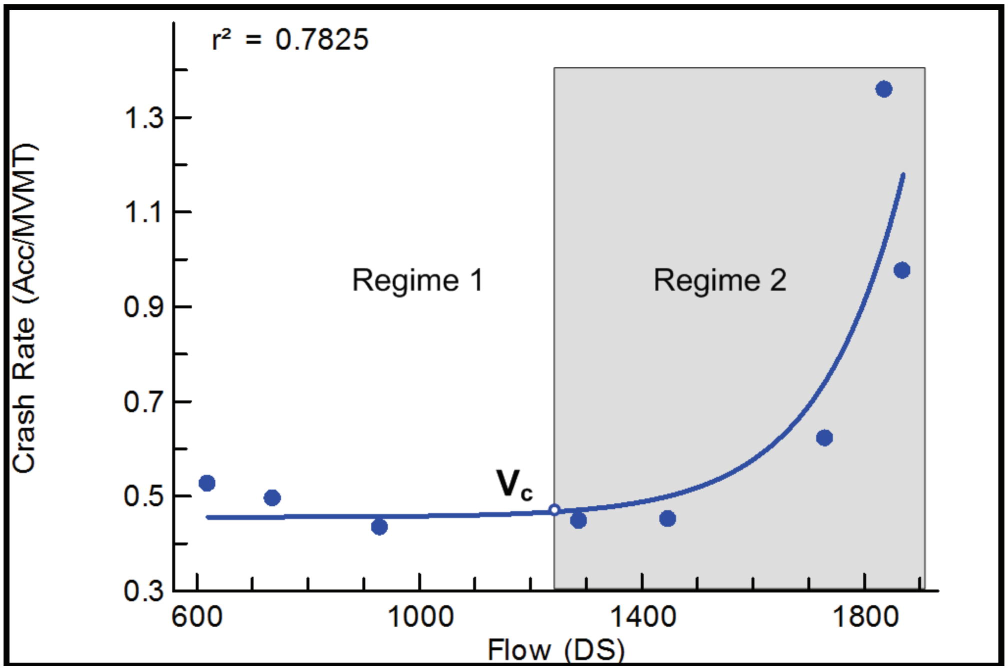


**Figure 7 Corridor-specific SPF with Regimes 1 and 2**

Regime 1 is characterized by low to moderate density and high speeds, where drivers are still able to compensate for increasing density. The increased focus on the driving task may possibly explain the fact that during Regime 1 the crash rate remains stable despite increase in density. Regime 2 is characterized by moderate to high densities without notable speed reduction where the combination of speed and density is such that more drivers are not able to compensate for driver's error and avoid a crash. In Regime 2 greater portion of near misses becomes crashes reflected by a sharp rise in the crash rate.

Figure 8 relates speed-volume-density/LOS curve for a freeway with free-flow speed of 70 mph with changes in crash rates reflected by the SPF. Incorporating LOS and accident rates in the SPF framework allows us to quantitatively relate safety to the degree of congestion. Understanding the relationship between traffic flow parameters and safety has important implications on the philosophy and policy of transportation planning, highway design criteria and freeway management.

A possible strategy to counteract the deficit of available deceleration distance associated with a mix of high speeds and short headways is to build additional lanes thus reducing volume and density per lane. The rest of the paper examines how adding lanes effects safety.

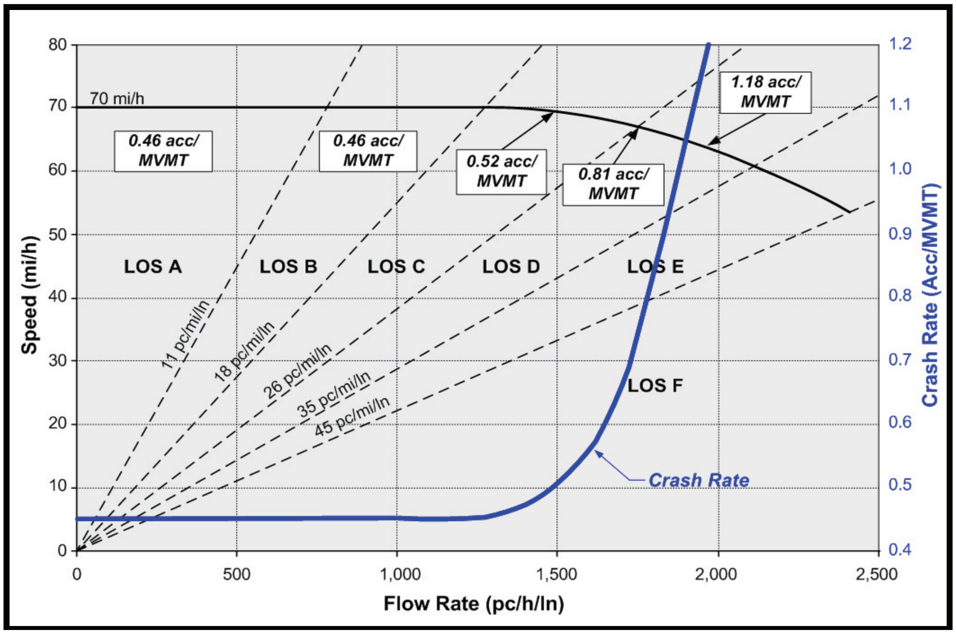


***Figure 8  Speed-Volume-Density/LOS and Total Crash Rates Relationship***

## EXPLAINING THE EFFECT OF ADDING LANES ON SAFETY USING SPF

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 using corridor specific SPF. C-470 Beltway around Denver is a 4-lane freeway facility carrying 1,870 vehicles per hour per lane (vphpl) during the peak period. Using the C-470 specific SPF we can estimate that at 1,870 vphpl the crash rate is 1.2 acc/mvmt. Proposed design alternative includes widening to 6-lanes and will result in redistribution of volume over 6 lanes instead of 4 lanes. This will produce a lower density of 1,247 vphpl following construction.  Using C-470 SPF and reduced volume per lane we can estimate safety performance after construction at a substantially lower crash rate of 0.46 acc/mvmt (Figure 9).

Calibrating the corridor specific SPF enables engineers and planners to estimate the effect of adding lanes on safety following construction by estimating crash rate at lower density per lane. However, the post-construction safety estimate above is likely to be somewhat optimistic. The estimate is based on the SPF for 4 lanes. It is plausible to expect, given the same volume/density of traffic per lane, all other things being equal, that a freeway with more lanes will experience higher crash rate. Nevertheless, even if a generous assumption of 25% increase in crash rate due to the increase in lane change related conflict opportunities described by Kononov et al (5) is made, the resulting crash rate of 0.59 acc/mvmt is still half of observed rate of 1.2 acc/mvmt.  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. Additionally, increased maneuverability associated with availability of more lanes tends to increase average speed of traffic and speed differential.

More precise estimate of the increase in crash rate attributed to the increase in the number of lanes should be obtained from the observational before and after studies using methodology described by Hauer (16). This question lends itself well to future research.

The reduction in volume and density per lane associated with widening is also associated with reduction in travel time. It is important to recognize, however, that the duration of improved safety and mobility following widening is defined by the pace of development and the amount of latent demand in the area.

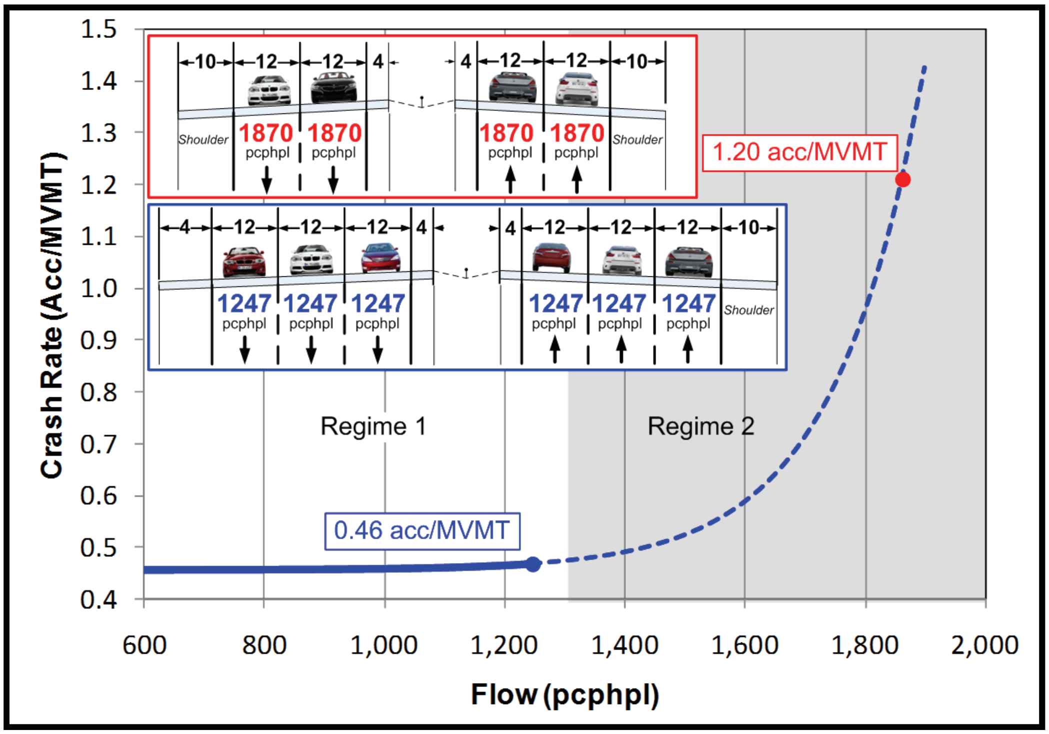


*Figure 9 Crash Rate Reduction due to Volume/Density Decrease from Adding Lanes*

## SUMMARY

The relationship between traffic flow parameters and safety has important implications on the philosophy and policy of transportation planning, highway design criteria and freeway management.

Empirical examination of the relationship of flow, density, and speed to crash rate on selected freeways in Colorado suggests that as flow increases crash rate initially remains constant until a certain critical threshold combination of speed and density is reached. Once this threshold is exceeded the crash rate rapidly rises. The rise in crash rate may possibly be explained by the fact that compression of flow without notable reduction in speed produces headways so small that it becomes very difficult or impossible to compensate for driver's error. A possible strategy to counteract the deficit of available deceleration distance associated with a mix of high speeds and short headways is to build additional lanes, thus reducing volume per lane. Incorporating LOS and accident rates in the corridor-specific SPF framework allows us to quantitatively relate safety to the degree of congestion. Calibrating corridor specific SPF also enables engineers and planners to estimate the effect of adding lanes on safety following construction by estimating crash rate at a lower volume and density per lane. It is important to recognize, however, that the duration of improved safety and mobility is defined by the pace of development and the amount of latent demand in the area. It is plausible to expect that given the same density of traffic per lane, all other things being equal, that a freeway with more lanes will experience higher crash rate.

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