Relationship Between Freeway Flow Parameters and Safety and Its Implication for Adding Lanes

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The decision to add lanes to a freeway is motivated by the need to relieve congestion. Practicing engineers and planners generally believe that the decreased congestion that results from adding lanes is associated with some degree of improved safety, yet the majority opinion of researchers is that accident rates increase as the number of lanes increases. In more than 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, with safety by calibrating corridor-specific safety performance functions. On the basis of an understanding of this relationship, a possible explanation of the effect that adding lanes has on safety is formulated. An empirical examination of the relationship of flow, density, and speed to the crash rate on selected freeways in Colorado suggests that, as the flow increases, the 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 the crash rate may be because an increase in density without a notable reduction in speed produces headways so small that it becomes difficult or impossible to compensate for driver error. This model suggests that, after the construction of additional lanes, crash rates initially decline because of the lower traffic volume and density per lane. However, as development and rerouting occur, freeways with more lanes are expected to have higher crash rates that are attributable to the increased opportunities for lane change–related conflicts.

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

This paper first examines the relationship of traffic flow parameters, such as volume, density, and speed, with safety by calibrating corridor-specific safety performance functions. Based on an understanding of this relationship, a possible explanation is formulated regarding the effect that adding lanes has on safety.

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Transportation Research Record: Journal of the Transportation Research Board, No. 2279, Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 118–123.
DOI: 10.3141/2279-14

RELATING FREEWAY FLOW PARAMETERS TO SAFETY

The relationships of speed and flow and of density and flow for a typical freeway segment are well understood at present and are documented by the successive editions of the *Highway Capacity Manual* (*1*). All recent freeway studies show that speed on freeways is insensitive to flow in the low to mid range. An increase in flow and density without a 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. observed that most research has focused on determining the relationship between crashes and annual average daily traffic and that little attention has been focused on the relationships of vehicle density, level of service (LOS), vehicle occupancy, volume to capacity ratio, and speed distribution (*2*). Zhou and Sisiopiku found that crash rates typically followed a U-shaped relationship when plotted as a function of the volume to capacity ratio (*3*). Traditional safety performance functions (SPFs) relate accident occurrence to annual average daily traffic. Persaud and Dzbik observed that a difficulty with this approach is that a freeway with an intense flow during rush periods would clearly have a different accident potential than a freeway with the same annual average daily traffic but with flow evenly spread throughout the day (*4*). Kononov et al. observed that on uncongested freeways, the number of crashes increases moderately with an increase in traffic; however, once a critical traffic density is reached, the number of crashes begins to increase at a much faster rate with an increase in traffic (*5*). Garber and Subramanyan related crashes to lane occupancy and concluded that peak crash rates do not occur during peak flows (*6*). Harwood noted that it would be extremely valuable to know how safety varies with the volume to capacity ratio and what volume to capacity ratios provide the minimum accident rate (*7*). Hall and Pendleton observed that knowledge of the definite relationship between the volume to crash ratio and the crash rate would help engineers and planners assess the implications for safety of highway improvements designed to increase capacity (*8*). Lord et al. concluded that, "Despite overall progress, there is still no clear understanding about the effects of different traffic flow characteristics on safety" (*2*).

Figure 1 [Exhibit 23-3 from the 2000 edition of the *Highway Capacity Manual* (*1*)] shows the speed–volume–density relationship and the LOS for basic freeway segments. The figure reflects the fact that drivers on modern freeways are slowing down very little or not at all as the LOS deteriorates from A to D. Considering that perception–reaction time and vehicle characteristics remain unchanged, yet there are considerably more vehicles in the same space traveling at substantially the same speed as before, an increased probability of crash

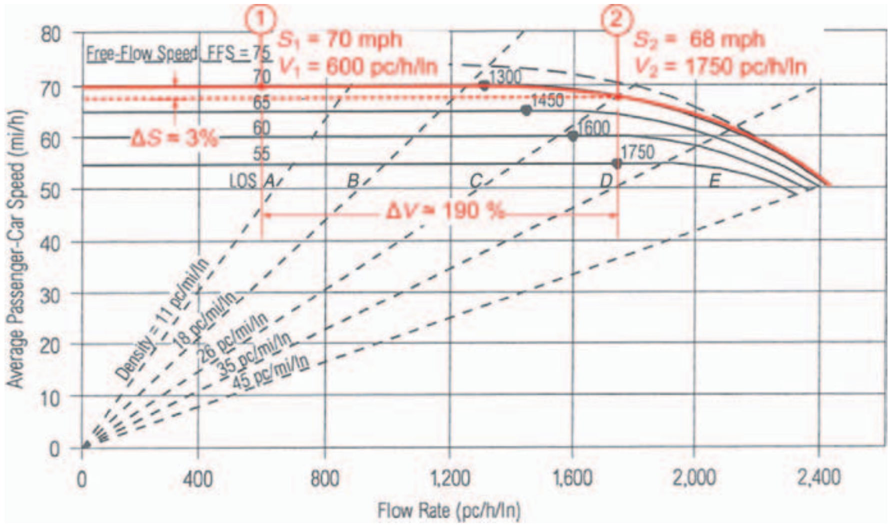

FIGURE 1 Speed–flow curves and LOS (*S* = speed; *V* = volume; *A–E* indicate levels of service; pc/h/ln = passenger cars per hour per lane; pc/mi/ln = passenger cars per mile per lane).

occurrence is highly plausible. This increase would be reflected by changes in the crash rate. For instance, a freeway with a free-flow speed of 70 mph at Point 1 carrying 600 passenger cars per hour per lan (pc/h/ln) (V_1) has a density (d_1) of 8.6 passenger cars per mile per lane (pc/mi/ln) and operates at LOS *A*. When congestion builds up to 1750 pc/h/ln (V_2) (the boundary between LOS C and LOS D), the resulting density rises to d_2, equal to 26 pc/mi/ln, and the operating speed drops only slightly to 68 mph.

As a transition is made from Point 1 to Point 2, densities that are almost three times greater can be observed, with a decrease in speed of only 3%. When these flow parameters are examined for a freeway with a free-flow speed of 55 mph, the volume rises from 600 pc/h/ln (density = 10.9 pc/mi/ln) to 1,750 pc/h/ln (density = 31.8 pc/mi/ln) without any speed reduction. The compression of flow without a corresponding reduction in speed is likely to have an adverse effect on safety; the calibration of this effect is explored in this paper.

RELATING NUMBER OF LANES TO SAFETY

The *Highway Capacity Manual* states that capacity increases proportionally with the number of lanes, with some adjustment for the increase in the free-flow speed as the number of lanes increases (*1*). What effect the number of lanes has on safety, however, is not fully understood at present.

Research conducted by Council and Stewart into the effect on safety of converting two-lane roads into four lanes found a 40% to 60% reduction in crashes as a result of the conversion to a four-lane cross section (*9*). Milton and Mannering found that increasing the number of lanes in rural Washington State led to more accidents (*10*). Noland and Oh rejected the hypothesis that geometric improvements, including an increase in the number of lanes, lane width, or median width, or a reduction in curvature, are beneficial for safety (*11*). Abdel-Aty and Radwan observed that crash rates increased with the number of lanes on urban roadway sections (*12*). Kononov et al., by comparing the slopes of SPFs described by their first derivatives, showed that adding lanes on urban freeways led to an increase in the crash rate (*5*). Garber concluded that accident rates increased with an increase in the number of lanes (*13*).

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

MODEL DEVELOPMENT

Preparation of Data Set

Hourly volume, operating speed, and free-flow speed data were collected from existing automatic traffic recording stations around the Denver, Colorado, metropolitan area for four-lane freeways and a segment of Interstate 70, which carries ski resort traffic through mountainous terrain. The mainline crash history was obtained from the Colorado Department of Transportation crash database for every hour over a 5-year period for every freeway in the data set. All crashes that occurred on ramps and cross roads were removed before fitting the models.

With the hourly volume on every segment matched with its crash history, it was possible to compute the crash rate in accidents per million vehicle miles traveled (acc/mvmt) for every hour of the 24-h period for all freeways in the data set. A composite graph that represents several Denver area four-lane freeways and demonstrates the changes in volume and crash rates throughout the day is presented in Figure 2.

Between the hours of midnight and 5 a.m., nearly 60% of all crashes involved alcohol or drug use or falling asleep at the wheel, as compared with only 4% during 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 in low volumes produces very high crash rates when compared with the daytime safety performance of the same segments. It may explain the U-shaped relationship identified by

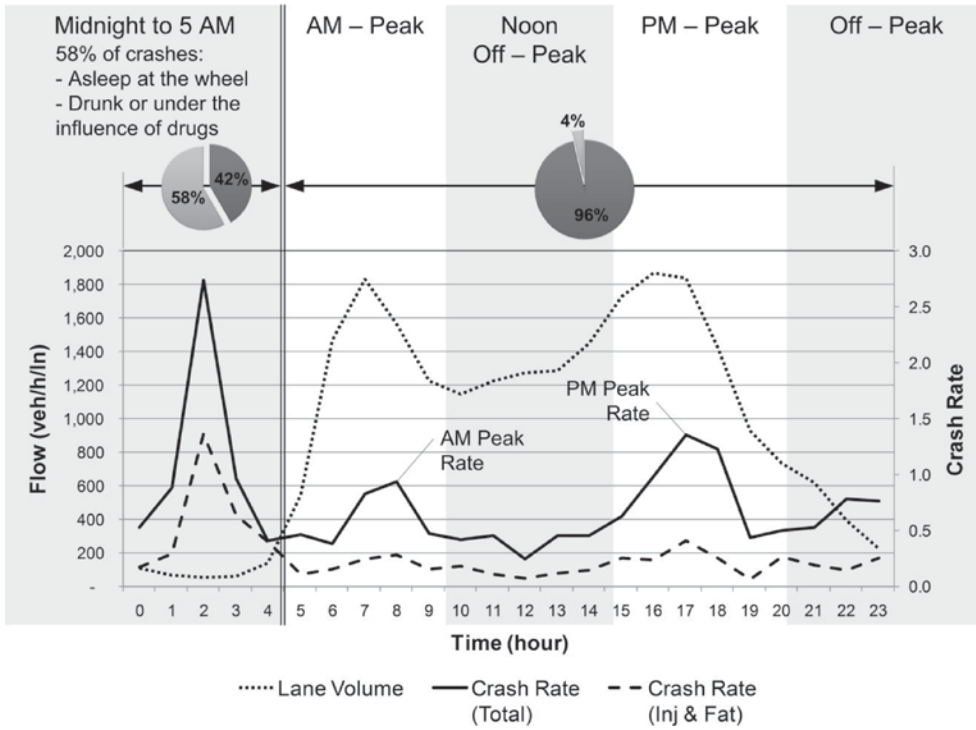

FIGURE 2 Changes in volume and crash rate over 24-h period on Denver area urban freeways (veh/h/ln = vehicles per hour per lane; inj & fat = injuries and fatalities).

Zhou and Sisiopiku (*3*). The impaired driver issue, a largely behavioral problem, is distinct from issues near or at peak times. In recognition of this, a portion of the data set that contained safety performance data between midnight and 5 a.m. was removed before the calibration of the corridor-specific SPFs. Additionally, the information in Figure 2 suggests that the afternoon peak is characterized by slightly higher crash rates than the morning peak. It may be speculated that commuters are more fatigued, more eager to get home from work, and less focused on the driving task at this time. Also, the higher crash rates may possibly be attributed to more secondary crashes that result from the longer duration of the afternoon peak period. With this in mind, separate corridor-specific SPFs were calibrated that contained the morning and afternoon peak periods on urban freeways, as well as a seasonal SPF for I-70 when carrying ski resort traffic.

Neural Networks

Corridor-specific SPFs that related freeway flow parameters with the crash rate were developed with neural networks, a subset of the general class of nonlinear models. Neural networks were used to analyze the data that consisted of observed univariate responses (Y_i), known to be dependent on corresponding one-dimensional inputs (x_i). Neural networks are not constrained by a preselected functional form and specific distributional assumptions. For this application, Y_i = crash rate (acc/mvmt) and $x_i = V$, where V is the hourly volume per lane [vehicles per hour per lane (veh/h/ln)]. The model becomes

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

where

$f(x_i, \theta)$ = nonlinear function relating Y_i to the independent variable x_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

$\varphi(u) = e^u/(1 + e^u)$, a logistic function;
$\beta_0, \beta_k, \gamma_k, \mu_k$ = parameters to be estimated for $i = 1, \ldots, K$; and
K = number of hidden units.

In this model, the β_ks are known as connection weights, and the μ_ks are the biases (*14*).

The function f is a 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 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

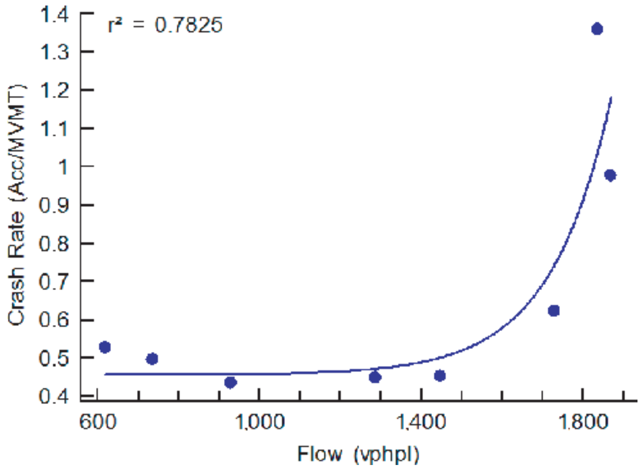

FIGURE 3 Corridor-specific SPF for C-470 beltway, p.m. (four lanes, 7 mi).

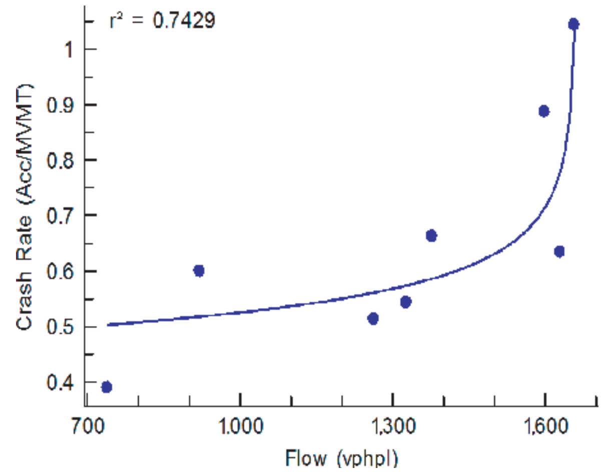

FIGURE 5 Corridor-specific SPF for I-270, p.m. (four lanes, 5 mi).

based on a general understanding of the underlying physical phenomenon. Additionally, the complexity of the model is most often chosen based on the generalized cross validation model-selection criterion. Cross validation is a standard approach for the selection of smoothing parameters in nonparametric regression, as described by Wahba (*15*). The overall model fit to the data is quite good (Figures 3–6).

The recognition that volume (V) is a product of traffic density (d) times speed (s) enables density to be considered in concert with speed when the relationship between flow characteristics and safety is examined. Figures 3–6 reflect these relationships for several four-lane freeways in the Denver metropolitan area and a heavily traveled rural freeway in a mountainous environment. The inventory of freeways used in this paper did not include any freeways that exceeded volumes of 1,900 veh/h/ln. This may explain why the reduction in crash rates associated with heavy congestion described by Kononov et al. (*5*) is not reflected in the functional form of corridor-specific SPFs in this study. Furthermore, the limited range of speeds represented prevents a detailed analysis of the way in which speed enters into the equation. Figures 3–6 suggest that the 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 a critical mass in physics. A possible explanation may be that if $V(ds)$ exceeds a certain critical threshold value (V_c), the available headway becomes too small for the prevailing speed to allow drivers to react effectively to changing traffic conditions. Furthermore, two distinct operational regimes can be observed in Figure 7, as well as in all the other corridor-specific SPFs: Regime 1, in which $V < V_c$, and Regime 2, in which $V > V_c$. The critical value of V_c can be estimated with a sliding interval analysis in the framework of the numerical differentiation technique described by Rao (*16*).

Regime 1 is characterized by low to moderate density and high speeds, and drivers are still able to compensate for increasing density. The increased focus on the driving task may explain the fact that during Regime 1 the crash rate remains stable despite an increase in density. Regime 2 is characterized by moderate to high densities without a notable speed reduction; the combination of speed and density is such that more drivers are unable to compensate for driver error and avoid a crash. In Regime 2, a greater portion of near misses become crashes, as reflected by a sharp rise in the crash rate.

Figure 8 relates speed, volume, density and LOS for a freeway with a free-flow speed of 70 mph with the changes in the crash

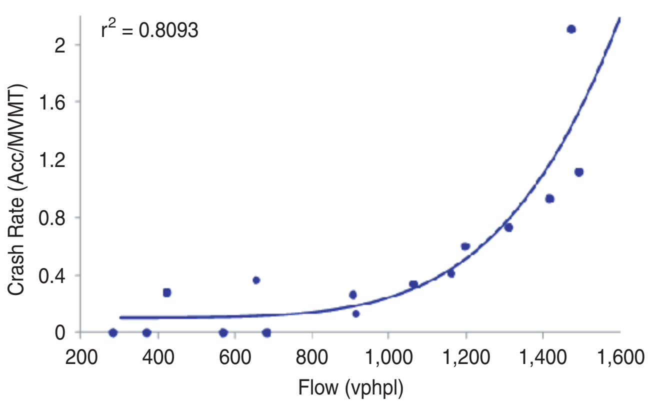

FIGURE 4 Corridor-specific SPF for I-70, winter weekend, eastbound flow (four lanes, 5 mi).

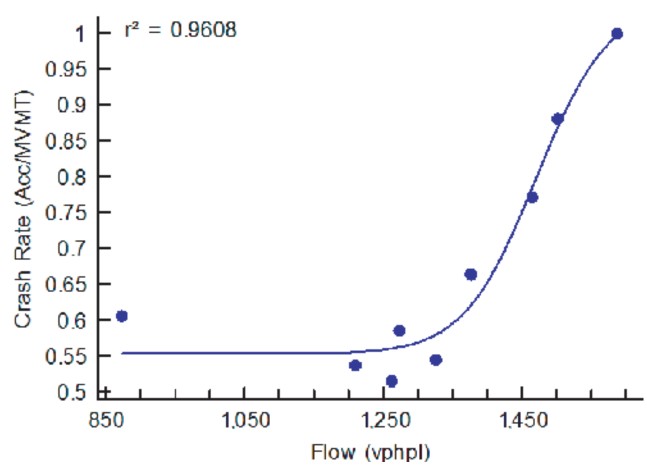

FIGURE 6 Corridor-specific SPF for I-270, a.m. (four lanes, 5 mi).

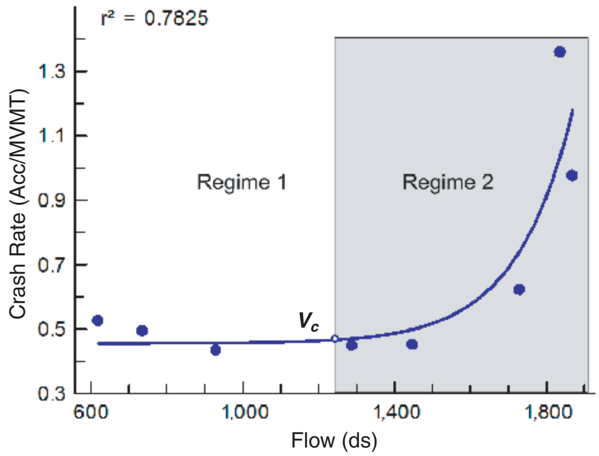

FIGURE 7 Corridor-specific SPF with Regimes 1 and 2.

rates reflected by the SPF. The incorporation of the LOS and the accident rates into the SPF framework allows safety to be quantitatively related to the degree of congestion. An understanding of the relationship between traffic flow parameters and safety has important implications for 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 and thus reduce volume and density per lane. The rest of the paper examines how adding lanes affects safety.

USING SPFs TO EXPLAIN EFFECT ON SAFETY OF ADDING LANES

The effect that 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. This question will be explored with a corridor-specific SPF. The C-470 beltway around Denver is a four-lane freeway facility carrying 1,870 veh/h/ln during the peak period. With the SPF specific to C-470, it can be estimated that at 1,870 veh/h/ln, the crash rate is 1.2 acc/mvmt. The proposed design alternative includes widening to six lanes and will result in the redistribution of volume over six lanes instead of four lanes. This will produce a lower density of 1,247 veh/h/ln after construction. With the C-470 SPF and the reduced volume per lane, the safety performance can be estimated 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 that adding lanes has on safety after construction through an estimation of the crash rate at the lower density per lane. However, the postconstruction safety estimate above is likely to be somewhat optimistic. The estimate is based on the SPF for four lanes. It is plausible to expect, given the same volume and density of traffic per lane and all other things being equal, that a freeway with more lanes will experience a higher crash rate. Nevertheless, even if a generous assumption of a 25% increase in the crash rate attributable to the increase in lane change–related conflict opportunities described by Kononov et al. is made (*5*), the resulting crash rate of 0.59 acc/mvmt is still half of the observed rate of 1.2 acc/mvmt. Although more research in this area is needed, this phenomenon may be explained as follows: as the number of lanes increases, the opportunity for lane change–related conflicts goes up. Additionally, the increased maneuverability associated with the availability of more lanes tends to increase the average speed of the traffic and the speed differential.

A more precise estimate of the increase in the crash rate attributable to the increase in the number of lanes should be obtained from the observational before and after studies through the use of the methodology described by Hauer (*17*). This question lends itself well to future research.

The reduction in volume and density per lane associated with widening is also associated with a reduction in travel time.

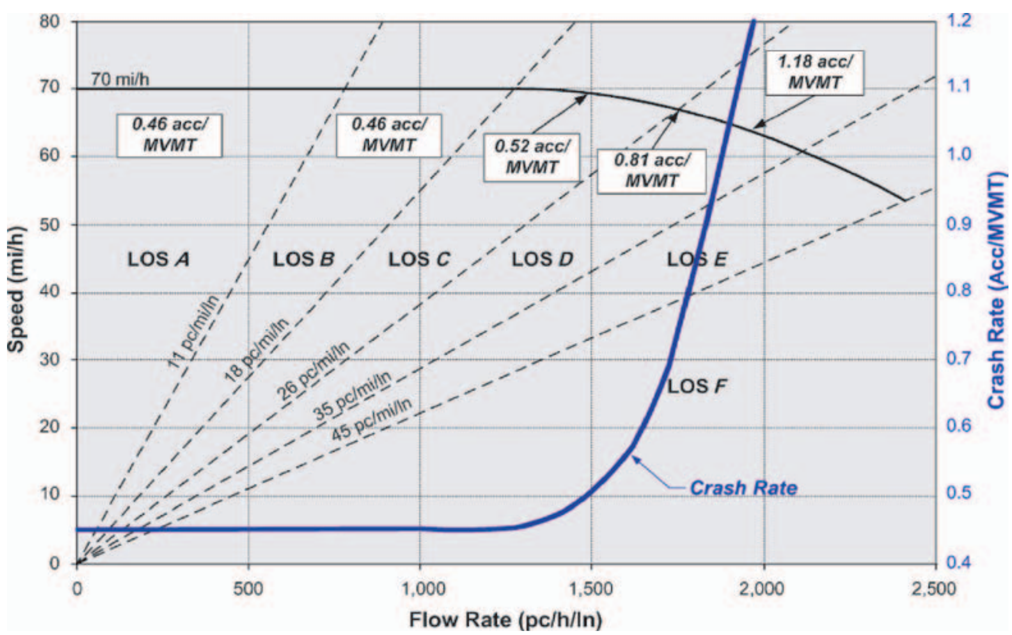

FIGURE 8 Relationship of speed–volume–density–LOS and total crash rates.

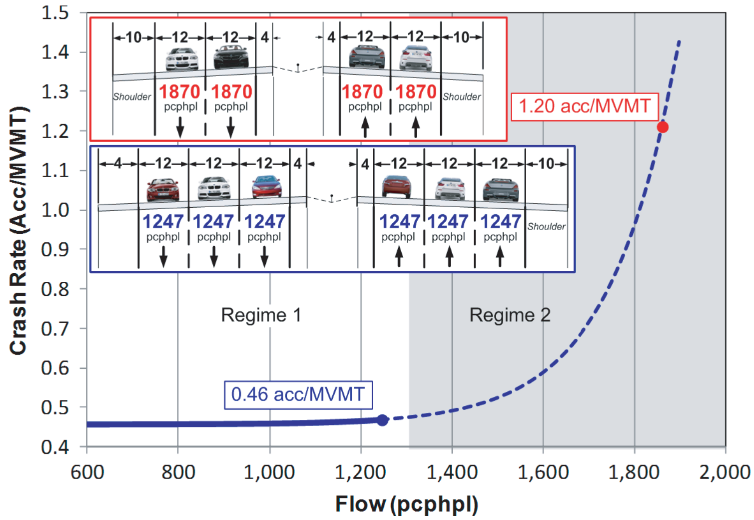

FIGURE 9 Crash rate reduction attributable to volume or density decrease from additional lanes.

However, the duration of the improved safety and mobility after widening is defined by the pace of development and the amount of latent demand in the area.

SUMMARY

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

An empirical examination of the relationship of flow, density, and speed to crash rate on selected freeways in Colorado suggests that as the flow increases, the 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 the crash rate may be explained by the fact that the compression of the flow, without a notable reduction in speed, produces headways so small that it becomes very difficult or impossible to compensate for driver 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 the volume per lane. The incorporation of LOS and accident rates into the corridor-specific SPF framework allows safety to be quantitatively related to the degree of congestion. Calibrating corridor-specific SPFs also enables engineers and planners to estimate the effect that adding lanes has on safety after construction through an estimation of the crash rate at a lower volume and density per lane. However, the duration of the 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 and all other things being equal, a freeway with more lanes will experience a higher crash rate.

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The Highway Safety Performance Committee peer-reviewed this paper.