Relationship Between Freeway Flow Parameters and Safety and Its Implications for Hard Shoulder Running

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Decisions to run traffic on freeway shoulders during peak periods are motivated by the need to relieve congestion. Practicing traffic engineers generally believe that the decreased congestion resulting from running traffic on hard shoulders (i.e., hard shoulder running) is associated with some unspecified degree of improved safety, yet the majority of researchers agree that accident rates increase as the number of lanes increase, even if full shoulders are provided. Despite many 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 with calibrated performance functions of corridor-specific safety. On the basis of an understanding of this relationship, a possible explanation of the effect on safety of hard shoulder running 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, 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 rises rapidly. This rapid rise in crash rate may be caused by an increase in density without a notable reduction in speed and the resultant small headways that make it difficult or impossible for drivers to compensate for error. This model suggests that during hard shoulder running, crash rates decline because of the lower traffic volume or density per lane and that the safety benefits of a reduced volume or density per lane outweigh the adverse effects of the lack of provision of a full shoulder.

Everything should be made as simple as possible, but not simpler. —Albert Einstein

The 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 (1). All recent freeway studies show that speed on freeways is insensitive to flow in the low to midrange. Increases in flow and density without a notable reduction in speed have a significant influence on safety. This influence, however, has not been studied extensively and to date has attracted only limited interest from researchers. Lord et al. observed that most research has focused on the relationship between crashes and annual average daily traffic, whereas little attention has been focused on the relationships of vehicle density, level of service (LOS), vehicle occupancy, the volume-to-capacity ratio, and speed distribution (2). Zhou and Sisiopiku found that crash rates typically follow a U-shaped relationship when they are 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 intense flow during peak periods would have a different accident potential than a freeway with the same annual average daily traffic but with flow evenly spread out 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 some critical traffic density is reached, the number of crashes begins to increase at a much higher 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-capacity ratio and crash rate would help engineers and planners assess the safety implications 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, which is Exhibit 23-3 from the 2000 edition of the Highway Capacity Manual (1), shows the speed–volume–density relationship and LOS for basic freeway segments. It shows that drivers on modern freeways slow down very little or not at all as the LOS deteriorates from A to D. When one considers that perception–reaction time and vehicle characteristics remain unchanged, even though considerably more vehicles are 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 a free-flow speed of 70 mph at Point 1 carrying 600 passenger cars per hour per lane [Volume 1 (V1)] has density d1 of 8.6 passenger cars per mile per lane (pc/mln) and operates at LOS A. When congestion builds up to 1,750 pc/mln (V2) (the boundary between LOS C and LOS D), the resulting density (d2) rises to 26 pc/mln and the operating speed drops only slightly to 68 mph.
As a transition from Point 1 to Point 2 is made, densities that are almost 3 times greater and a decrease in speed of only 3% are observed. When these flow parameters are examined for a freeway with a free-flow speed of 55 mph, the volume rises from 600 vehicles per hour (density $= 10.9$ pc/mi/ln) to 1,750 vehicles per hour (density $= 31.8$ pc/mi/ln) without any speed reduction. Compression of flow without a corresponding reduction in speed is likely to have an adverse effect on safety; calibration of this effect is explored in this paper.

SAFETY EFFECT OF HARD SHOULDER RUNNING

Decisions to run traffic on freeway shoulders (i.e., hard shoulder running) during peak periods are motivated by the need to relieve congestion. Practicing traffic engineers generally believe that decreased congestion resulting from hard shoulder running is associated with some unspecified degree of improved safety, yet the majority opinion among researchers is that accident rates increase with an increase in the number of lanes, even if full shoulders are provided. Despite many years of modern road building, these conflicting views have not been reconciled.

From the standpoint of traffic operations, hard shoulder running approximates addition of through lanes to the freeway, with recognition that some adjustment to the base free-flow speed must be made to account for the reduced lateral clearance and the increased number of lanes. According to the Highway Capacity Manual, lateral clearance of less than 6 ft reduces the base free-flow speed, whereas the addition of lanes increases it (1). It is also known from the Highway Capacity Manual that capacity is increased 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 on the safety effects of the conversion of two-lane roads to four lanes conducted by Council and Stewart found 40% to 60% reductions in crashes as a result of conversion to a four-lane cross-section (9). Milton and Mannering found that an increase in the number of lanes in rural Washington State led to more accidents (10). Noland and Oh rejected the hypothesis that geometric improvements, including increases in the number of lanes, lane width, and median width and a reduction in curvature, are beneficial for safety (11).

Garber concluded that accident rates increase with an increase in the number of lanes (12). Kuhn noted that European highway agencies realized both safety and mobility benefits from hard shoulder running, whereas the safety benefits of the deployment of traffic on hard shoulders in the United States are inconclusive (13). Aron et al. examined the safety benefits of the use of the hard shoulder on a motorway in Paris and concluded that a reduction in congestion results in a decrease in the accident count but expressed concerns about accident migration (14).

Fuhs cautioned that safety is generally the greatest concern when strategies in which traffic is run on the shoulder are implemented, because use of the shoulder as a travel lane results in the loss of a continuous emergency refuge area (15). Geisterfeldt examined the effect of temporary use of the hard shoulder in the German state of Hesse (16). He observed increased capacity in the range of from 20% to 25% and concluded that use of the hard shoulder does not affect road safety.

Thomas observed that initial safety concerns of hard shoulder running were dispelled by the discovery that fewer accidents took place, as drivers were not running in congested traffic and making risky maneuvers (17). In the most recent findings from a 3-year safety study of hard shoulder running on the M42 motorway by Britain’s Highways Agency, Unwin showed a 56% reduction in accidents involving personal injuries (18).

Bauer et al. concluded that addition of an additional lane to convert an urban freeway from four to five lanes in one direction by reducing existing lane and shoulder widths resulted in 10% to 11% increases in the rates of all crashes (19). Their findings, however, were influenced by the fact that the added lanes were used as high-occupancy vehicle and not general-purpose lanes. As a result, the traffic was not evenly distributed among the lanes, which detracted from the benefits of hard shoulder running.

This paper first examines the relationship of traffic flow parameters, such as volume, density, and speed, to safety by calibration of...
corridor-specific SPFs on the basis of hourly volume. On the basis of an understanding of this relationship, a possible explanation of the effect on safety of hard shoulder running is formulated.

MODEL DEVELOPMENT

Data Set Preparation

Hourly volume, operating speed, and free-flow speed data were collected from existing automatic traffic recording stations on four-lane freeways and a segment of Interstate 70 that carries traffic to ski resorts in mountainous terrain around the Denver, Colorado, metropolitan area. The main-line 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 crossroads were removed before fitting of the models.

Matching of the hourly volume on every segment with its crash history enabled computation of the crash rate (in numbers of accidents per million miles traveled) for every hour of the 24-h period for all freeways in the data set. A composite graph representing several Denver area four-lane freeways and showing changes in volume and crash rates throughout the day is presented in Figure 2.

Nearly 60% of all crashes that occurred between midnight and 5 a.m. but only 4% of those that occurred during the rest of the day involved alcohol use, drug use, or falling asleep at the wheel. Such a dramatic difference in driver performance abilities and crash causality suggests that they are qualitatively different phenomena. A mix of impaired and fatigued drivers with low volumes produces very high crash rates between midnight and 5 a.m. compared with the daytime safety performance of the same segments. This finding may possibly explain the U-shaped relationship identified by Zhou and Sisiopiku (3).

The impaired driver issue, a largely behavioral problem, is distinct from issues that present problems near or at peak times. With recognition of this, a portion of the data set containing safety performance data for the period between midnight and 5 a.m. was removed before calibration of the corridor-specific SPFs. Figure 2 also 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, less focused on the driving task, and eager to get home from work. The higher crash rates may also be attributed to the larger number of secondary crashes that result from the longer duration of the p.m. peak period. With this in mind, separate corridor-specific SPFs for morning and afternoon peak periods on urban freeways and a seasonal SPF for the section of I-70 carrying traffic to ski resorts were calibrated.

Neural Networks

Corridor-specific SPFs relating freeway flow parameters to the crash rate were developed by the use of neural networks, which are a subset of the general class of nonlinear models. Neural networks were used to analyze the data, which 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 the current application, \( Y_i \) is the crash rate (in numbers of accidents per million vehicle miles traveled) and \( x_i \) is the hourly volume per lane \( (V_i; \text{in numbers of passenger cars per hour per lane}) \). The model becomes

![FIGURE 2](image_url) Changes in volume and crash rate over a 24-h period on Denver area urban freeways (vphpl = vehicles per hour per lane; inj & fat = injuries and fatalities).
\[ Y_i = f(x_i, \theta) + e_i \]

where

\[ f(x_i, \theta) = \text{nonlinear function relating } Y_i \text{ to the independent variable } x_i \text{ for the } i\text{th observational unit}, \]

\[ \theta = p\text{-dimensional vector of unknown parameters, and} \]

\[ e_i = \text{sequence of independent random variables}. \]

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. Hidden units represent intermediate computational layers between the input and the output of the neural network. The form of the model is

\[
f(x, \theta) = \beta_0 + \sum_{k=1}^{K} \beta_k \phi(x \gamma_k + \mu_k) = \sum_{k=1}^{K} \beta_k \phi(u_k)
\]

where \( \beta_0, \beta_k, \gamma_k, \text{ and } \mu_k \) are parameters to be estimated for \( i = 1, \ldots, K; \)

\( K = \text{number of hidden units; and} \)

\( \phi(u) = e^u/(1 + e^u) \), which is a logistic distribution function.

\( \beta_k \)s are known as connection weights, and \( \mu_k \)s are biases (20).

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

The parameters \( \beta_0, \beta_1, \gamma_1, \text{ and } \mu_1 \) 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. A \( K \) value of 1 was chosen on the basis of a general understanding of the underlying physical phenomenon. In addition, 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 (21). The overall fit of the model to the data is quite good (Figures 3 to 6).

Recognition that volume \( V \) is a product of traffic density \( d \) and speed \( s \) enables density to be considered in concert with speed as the relationship between flow characteristics and safety is examined. Figures 3 to 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 with volumes that exceed 1,900 vehicles per hour per lane (vphpl). This fact may explain why the reduction in crash rates associated with heavy congestion described by Kononov et al. is not reflected in the functional form of corridor-specific SPFs in this study (5). Furthermore, the limited range of speeds represented prevents a detailed analysis of the way in which speed enters into the equation. The data in Figures 3 to 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 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 on all other corridor-specific SPFs: Regime 1, in which $V$ is less than $V_c$, and Regime 2, in which $V$ exceeds $V_c$. 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 (22).

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

Figure 8 shows the speed–volume–density/LOS curve for a freeway with a free-flow speed of 70 mph, with changes in crash rates reflected by the SPF. Incorporation of LOS and accident rates into the SPF framework allows safety to be quantitatively related to the degree of congestion. Understanding of the relationship between traffic flow parameters and safety has important implications for transportation planning, highway design, and freeway management philosophy and policies.

A possible strategy to counteract the deficit of available deceleration distance associated with a mix of high speeds and short headways is to allow hard shoulder running during peak periods, which would thus reduce the volume and density per lane. The rest of the paper examines how hard shoulder running affects safety.

**SPF AND EFFECT ON SAFETY**

The effect that hard shoulder running 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 is explored with corridor-specific SPFs. The C-470 Beltway around Denver is a four-lane freeway facility carrying 1,870 vphpl during peak periods. Use of the C-470-specific SPF allows estimation of a crash rate of 1.25 crashes per million vehicle miles traveled with a volume of 1,870 vphpl. The proposed use of the hard shoulder as a travel lane during peak periods will result in redistribution of the volume over six lanes instead of four. This redistribution will produce a smaller volume of 1,247 vphpl after construction. With the C-470 SPF and the reduced volume per lane, after deployment of traffic on hard shoulders, safety performance can be estimated to be a substantially lower crash rate of 0.46 crash per million vehicle miles traveled (Figure 9).

Calibration of the corridor-specific SPF enables engineers and planners to estimate the effect on safety of hard shoulder running after traffic is deployed by estimation of a crash rate with a lower density per lane. However, the postdeployment safety estimate described above is likely to be somewhat optimistic. The estimate

![Corridor-specific SPF for I-270 (p.m., lane volume).](image1)

![Corridor-specific SPF with Regimes 1 and 2 (DS = density times speed).](image2)
is based on the SPF for freeways with full shoulders. According to FHWA’s Crash Modification Factors Clearinghouse, provision of full shoulders will reduce crashes by 20% to 25% (23). Nevertheless, even if a conservative assumption of a 25% increase in crash rate because of a lack of shoulders is made, the resulting crash rate of 0.58 crash per million vehicle miles traveled (Figure 10) is still half of the observed rate of 1.20 crashes per million vehicle miles traveled. The crash reduction from hard shoulder running predicted by the corridor-specific SPF is similar to the 56% observed in the safety study of the M42 motorway by Britain’s Highways Agency (18).

Use of corridor-specific SPF suggests that the benefit of crash reduction is likely to outweigh the adverse effect of not having full shoulders. It must be recognized, however, that the effect on safety
of hard shoulder running is dependent on the number of lanes and the degree of congestion. The safety benefit of hard shoulder running on a four-lane freeway is expected to be greater than that on six-lane facilities. The greater benefit may be explained by the fact that density is decreased by 50% on the four-lane freeway but by only 33% on the six-lane freeways.

**SUMMARY**

The relationship between traffic flow parameters and safety has important implications for transportation planning, highway design, and freeway management philosophy and policies. 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 will remain constant until a certain critical threshold combination of speed and density is reached. Once this threshold is exceeded, the crash rate rises rapidly. The rise in crash rate may be explained by the fact that compression of flow without a notable reduction in speed produces headways so small that it becomes 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 deploy traffic on hard shoulders during peak periods, thus reducing the volume per lane. Incorporation of LOS and accident rates in the corridor-specific SPF framework allows quantification of the relationship of safety to the degree of congestion. Calibration of a corridor-specific SPF also enables engineers and planners to estimate the effect of hard shoulder running by estimating crash rates at a lower volume and density per lane.

Use of the corridor-specific SPF suggests that the benefit of crash reduction is likely to outweigh the adverse effect of not having full shoulders. The adverse effect of not having shoulders can be further moderated by construction of pullouts, the increased presence of courtesy patrols, and the use of variable speed limits and real-time queue warnings. It must be recognized, however, that the effect on safety of hard shoulder running is dependent on the number of lanes and the degree of congestion.

**REFERENCES**


