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ARTICLE

Analysis of Work Zone Traffic Behavior for Planning Applications

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ABSTRACT Understanding work zone traffic behavior is important for the planning and operation of work zones. The objective of this paper is to develop a mathematical model of work zone traffic flow elements by analyzing the relationships between speed, flow, and density that can be used to estimate the capacity of work zones. Traffic flow data were collected from 22 work zone sites on South Carolina interstate highways. The scatter plots of the collected data demonstrate that the relationship between speed and density does not follow Greenshields' linear model. A non-linear hyperbolic model was developed to describe the relationship between speed and density. Using this model the capacity of a work zone was estimated to be 1550 passenger cars per hour for 2-lane to 1-lane closures. Adjustments to this capacity value to consider other types of vehicle as well as the work zone intensity are provided. Highway agencies can use this estimated capacity along with anticipated traffic demand to schedule work zone operations to avoid long periods of over-saturation.

The tapered approach to work zone lane closures used by South Carolina is similar to methods used in work zones throughout the world. The authors believe that the methodology described in this paper for modeling work zone traffic as well as estimating work zone capacity is transferable to other countries. The conversion of actual volumes to passenger car equivalents may have to be modified due to the significant differences in traffic makeup between the United States and other countries.

KEY WORDS: Base capacity; non-linear model; speed–flow relationship; speed–density relationship; work zone

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Introduction

Construction and maintenance activities take place in work zones along highways, reducing capacity and resulting in traffic congestion and delays. This is an international problem that transportation agencies everywhere responsible for the construction and maintenance of highways must consider in the planning of work zone operations. In May, 2003, the South Carolina Department of Transportation (SCDOT) under a funding agreement with the United States Federal Highway Administration (FHWA) initiated a research study to quantitatively examine the development and implementation of a methodology for use in determining an updated lane closure policy within work zones along South Carolina's interstate highway system. Specific emphasis of the study would focus on determination of the number of vehicles per hour per lane (vphpl) that can pass through open lanes in short-term interstate work zone when one or more lanes have been closed with minimum or acceptable levels of delay. This paper presents research results based on this project.

The literature on traffic behavior on highways is widespread. The model developed by Greenshields in 1934 has served as a milestone in describing the fundamental relationships between flow, density and speed on highways (Greenshields, 1934). This single-regime model was based on observing speed–density measurements obtained from an aerial photographic study (May, 1990). Other researchers, such as Greenberg (1959), developed multi-regime models based on non-linear relationships between speed and density. Multi-regime models provide a considerable improvement over the single-regime one proposed by Greenshields in that they introduce the idea of generalizing traffic stream models into families by considering different traffic parameters. The multi-regime models attempt to more closely replicate observed/measured relationships between major traffic flow parameters; however, none of these theoretical models perfectly estimate speed, density and flow as observed under field conditions. In Greenberg's model, as traffic operations move from congested to uncongested situations, a rapid reduction in the maximum flow occurs. Similarly, when queuing conditions occur, there is a rapid decline in capacity due to the turbulence caused in the traffic flow (Hall & Agyeman-Duah, 1991).

Most of the research of non-linear models has been conducted on traffic flow patterns on freeways under normal daily conditions. However, not many studies have involved traffic flow in work zones. Investigations in this area are important because non-linear models reflect real-world conditions more accurately in many situations than linear models.

In the study of traffic flow, as in other areas, new analytical techniques frequently produce findings that are not easily explained using conventional theories. The latest investigations have introduced the concept of three-dimensional models of traffic stream characteristics, allowing for the three variables of speed, density, and flow to be studied in three-dimensional space, rather than in two-dimensional space. This method affords the possibility for identifying whether the relationships follow two-dimensional traditional traffic flow theory (Gilchrist & Hall, 1989).

Capacity as defined in the US Transportation Research Board's *Highway Capacity Manual (HCM)* is the 'maximum rate of flow that can be accommodated on a given traffic facility under prevailing conditions' (Transportation Research Board, 2000). This means that a stated capacity for a roadway is the rate of flow that can be continually attained during peak periods for which sufficient demand exists. This definition does not fully explain how to estimate capacity and what factors influence capacity under real-world conditions. Many studies have been conducted in the past to estimate the capacity and the factors influencing it and there have been several methods used to determine traffic capacity in a work zone. The earliest work in this area was the study of hourly volume under congested traffic conditions by the Texas Transportation Institute (Dudek & Richards, 1982). Research in North Carolina used the flow rate at which traffic behavior quickly changes from uncongested to queued conditions to estimate highway capacity in work zones (Dixon & Hummer, 1995). More recently, a study in Indiana used the traffic flow rate just before a sharp speed drop followed by a sustained period of low vehicle speed and fluctuating traffic flow rate (Jiang, 1999). Researchers in Iowa estimated capacity using the mean queue discharge flow rate from the bottleneck at the end of the transition area (Maze *et al.,* 2000).

One earlier study conducted by Chin and May (1991) examined the speed–flow relationship at the Caldecott Tunnel, the freeway section of California State Highway 24. Using these results, the study's researchers proposed a set of speed–flow curves that differed from those in the *HCM*. This research was conducted using only uncongested flows, which are the upper segments of the speed–flow curves, and found that work zone scenarios differ from these relationships in many aspects. The mean passenger car speed was used as a speed variable instead of the average travel speed. The capacity under ideal conditions, independent of the design speed of the highway, was found to be 2200 passenger cars per hour per lane (pcphpl). Lane width, lateral clearance, median type, and the frequency of access points did not affect the capacity; rather it affected the operating speed of the highway.

Research conducted by Krammes and Lopez (1992) estimated the capacity values for short-term freeway work zone lane closures using the data collected at 33 work zone sites in Texas between 1987 and 1991. Data were collected for five different lane closure configurations including (3 to 1), (2 to 1), (4 to 2), (4 to 3), and (5 to 3), noting that (3 to 1) represents that out of three lanes in one direction, one lane is closed. Data collection consisted of more than 45 hours of capacity counts at 33 different freeway work zones with short-term lane closures. The counts were taken as vehicles entered the work zone area through the transition area to minimize variability caused due by differing numbers of lanes between sites. The average capacities for five-lane closure configurations for the data collected were plotted to find out the overall average capacity combining all types of lane closure configurations. The research recommended that the base capacity value represents conditions in which the impacts of ramps were negligible, and the effect of ramps needs to be treated separately. A base capacity value of 1600 pcphpl was recommended for all short-term freeway lane closure configurations, which is compared to the standard accepted capacities of 2200 pcphpl for freeways and 1900 passenger cars per hour per green per lane (pcphgpl) for signalized intersections. These values represent queue discharge rate for freeway facilities, and saturation flow rate for signalized intersections. Several adjustments were made to the base capacity value including adjustments for intensity of work activity, effect of heavy vehicles, and the presence of ramps when applying to specific work zone locations.

Unlike previous studies, Maze *et al.* (2000) evaluated the capacity of lane closures and driver behavior within work zones on the rural interstates of Iowa, focusing on the rate at which queues develop and dissipate. This research determined that the approximate capacity of the Iowa rural work zone lane closures varied from 1400 to 1600 passenger car equivalents (PCEs) per hour per lane. Similarly, Jiang (1999) focused on the delays caused in work zones on freeway facilities in Indiana. His study measured delays caused by the deceleration of vehicles when approaching work zone areas, low speeds through the work zone area, the time required for vehicles to return to freeway speed and the queues formed at the work zones. Several delay equations, which differentiate when the approaching traffic is below and above the work zone capacity for all the above kinds of situations, were developed for these studies.

Kim *et al.* (2001) developed a new method for estimating the capacity of work zones. Their study investigated various factors influencing work zones, leading to the creation of a multiple regression model for estimating capacity. This model was a function of several independent factors such as number of lanes closed, the proportion of heavy vehicles, and the grade and intensity of the work zones. When compared side by side, this model performed better than several other capacity models in the *HCM*.

Adeli and Jiang (2003) proposed an innovative method using neuro-fuzzy logic to estimate the capacity for freeway work zone. As many as 17 factors that possibly affect the work zone capacity was considered in their case study. The authors applied back propagation neuro-network to search for associated parameters used in fuzzy logic, which had a Gaussian-shaped membership function. The case study indicated that proposed method performed accurately, especially when only partial parameters are available. They also declared the advantage of their method in terms of incorporating large number of factors and no requirement of prior knowledge about these factors.

Chitturi and Benekohal (2004, 2005) used selected software programs and analyzed the effect of lane width on work zone traffic flow. Quewz, FRESIM and QuickZone models were used to analyze capacity, queuing and delay in construction work zones and compared results to field collected data. The findings indicated that none of the programs produced results that were reasonably close to observed field data.

As this review suggests, several factors play a role in speed–flow relationships and in the capacity of work zones. While there are numerous methods for modeling traffic flow and the capacity of work zones, there is not a consensus on which method provides the best estimate of actual traffic flow conditions. This research project focused on developing models predicting relationships between speed, flow, and density based on non-linear approaches in an effort to more accurately model traffic and estimate capacity of work zones. Specifically, the objectives of the research on which this paper is based were:

- to understand work zone traffic behavior using non-linear approaches to modeling the speed–flow–density relationships; and
- to develop capacity thresholds for work zone lane configurations, where out of two lanes one lane is closed (a 2 to 1 lane closure).

Methodology and Data Collection

This paper is based on data collected at 22 work zones, which extended over a period of approximately one year. These work zone projects located throughout the state of South Carolina concentrated on four-lane highways (two lanes in each direction) involving short-term lane closures (<24 hours). Volume data were collected using a camera combined with automated digital image processing or manual tabulation techniques. Because many of the projects were at night, much of the video data had to be processed manually to determine volumes and vehicle classification. The truck percentage varied between 3 and 40% in the work zones. A database created in Microsoft Excel included information on different traffic stream parameters based on lane configurations and queues. Several scatter plots were generated for speed–density, speed–flow and flow–density to understand the fundamental relationships of traffic stream characteristics in work zones. Statistical Analysis Software (SAS), which is a comprehensive statistical and graphical package including modules for several types of specialized analysis, was used to generate graphs of these fundamental relationships (SAS, 2004).

Data Analysis

Data analysis included data preparation, developing relationship between traffic flow parameters and capacity estimations.

Data Preparation

As the results from the project demonstrated, truck volume has a significant effect on the traffic flow in the work zones. When approaching these areas, trucks often occupy all available lanes, blocking passenger cars and causing delays. Therefore, the impact of trucks is a significant consideration in minimizing the effect of work zones on traffic flow. Each truck is mathematically converted into passenger cars with a conversion factor called *PCE*. By measuring the distance from the rear end of a leading vehicle to the rear of a trailing one, referred to as the headway, these PCEs were determined for trucks and recreational vehicles. PCEs reflect the number of passenger cars that will occupy the space of these larger vehicles in a specific traffic stream. Comparing the headways for passenger cars and trucks, the PCE value was determined. These PCEs were categorized based on speeds of the vehicles traveling in the work zones. The following results generated from earlier studies (Narapsetty, 2004) were used in performing the analysis for this research, as shown in Table 1. Narapsetty found that PCE values for trucks are a function of speed. This traffic phenomenon is supported by the findings of Chitturi and Benekohal (2004, 2005). Chitturi and Benekohal suggest that predicting speed reductions should be a function of vehicle size and not be a constant value for all vehicle classifications.

After this conversion, consecutive and discrete flows were calculated. The consecutive flow for one-hour intervals was achieved by adding 12 consecutive five-minute flows, with the speed corresponding to this

Table 1. Average PCE values for trucks used for the analysis (Narapsetty, 2004)

Speed (mph)	PCE for trucks
0–15	2.47
15–30	2.22
30–60	1.90

flow value being the average of the 12 five-minute speeds. The calculated flow thus represented an actual hourly volume. The discrete flow for a one-hour interval was calculated by projecting the five-minute flow value over an hour, with the speeds being those calculated for the five-minute intervals. This procedure for calculating consecutive and discrete flows was carried out for 2 to 1 lane closures. Using the basic definition of density, i.e. density equals flow divided by speed, consecutive and discrete densities for one-hour intervals for all the projects, including different lane configurations, were calculated. Once the data for all parameters, i.e. speed, density, and flow, were determined, scatter plots were generated considering two variables at a time for both consecutive and discrete situations to analyze their relationships.

Relationships between Traffic Flow Parameters

Flow–density relationships. The scatter plot of flow versus density for all 2 to 1 lane projects is shown in Figure 1, with the values in this graph being the discrete values generated by projecting five-minute periods over an hour for all of these projects. The flow here is in terms of pcphpl, considering heavy vehicles. The overall relationship between flow and density failed to follow the Greenshields' parabolic path. The maximum flow values were found to be approximately around 1800 pcphpl based on a visual interpretation of the graph.

Figure 2 shows the plot of flow versus density for 2 to 1 lane projects using consecutive values generated by adding 12 successive five-minute periods, which reflects actual hourly flow and average density. This data follows the trends as described in Figure 1, with a slight variation in the maximum flows observed. The flows remained steady above the free-flow speeds and visually suggested the highest values to be approximately 1700 pcphpl. There were fewer data points in this graph than the number of discrete values in Figure 1, as one point represents 12 records in the original field data.

Speed–flow relationships. To estimate the capacity, several graphs of the relationship between speed and flow were plotted. Figure 3, which represent speed versus flow for all 2 to 1 lane closures, was developed using discrete five-minute flow values projected to hourly flows by

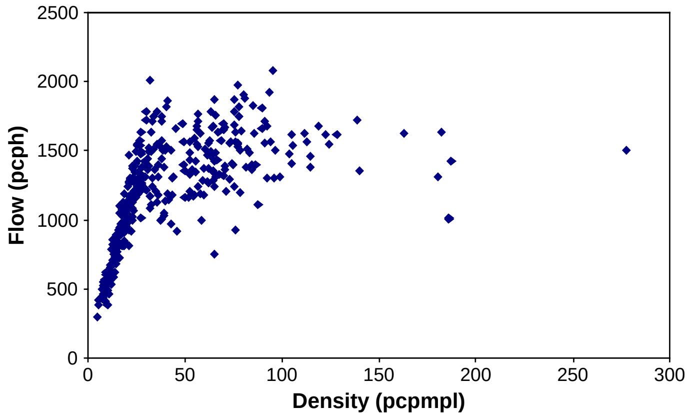

Figure 1. Graph of flow versus density (discrete five-minute flows)

multiplying each by 12. Even though the data is significantly scattered, it appears to follow Greenberg's non-linear flow pattern, in that the upper section of the graph is nearly stable under capacity, while the lower section exhibits a rapid drop in speeds. This graph identifies the capacity to be approximately 1700 pcphpl.

Similarly, Figure 4 shows the same trend for speed versus consecutive flow for all 2 to 1 lane closures. Here the flow is based on actual hourly volume calculated by adding 12 consecutive five-minute flow values and using weighted-average speeds for these periods.

Two-dimensional model for speed and flow. To model speed versus flow, this research began with a two-dimensional model using SAS, which was developed directly from field data. SAS was successful in

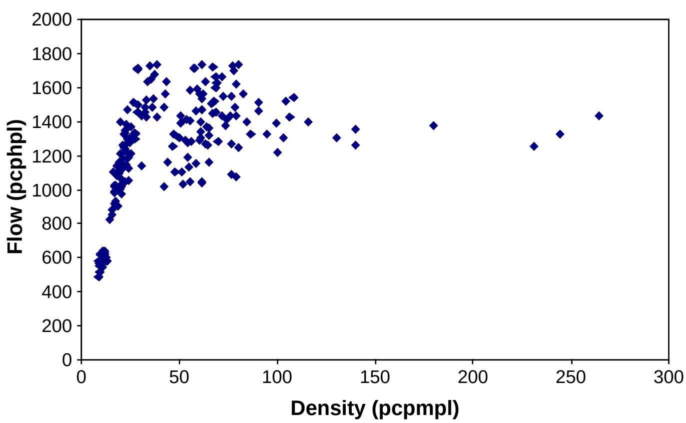

Figure 2. Graph of flow versus density (12 consecutive five-minute periods)

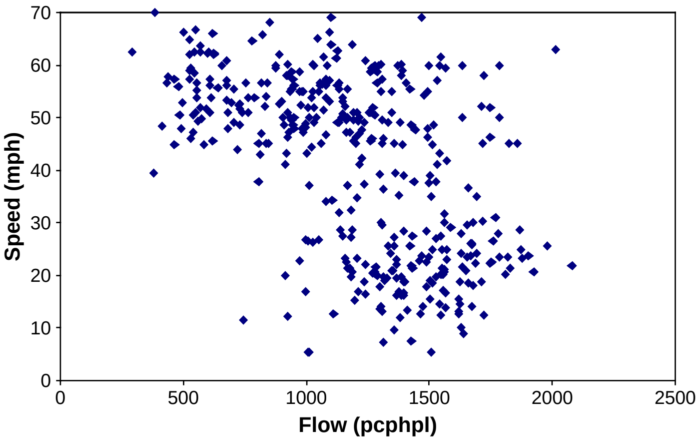

Figure 3. Graph of speed versus flow (discrete five-minute flows)

generating the model with necessary statistical calculations but failed in providing statistically significant relationships. Figure 5 shows the SAS-generated model for speed versus discrete flow for all 2 to 1 lane projects. It was noted that the R^2 value was very low because the data was widely spread throughout the graph. The data failed to follow Greenshields' parabolic path because of the few data points between the speed range of 30–45 mph and below 20 mph.

Three-dimensional model for speed, flow and density. The authors attempted to find the relationship between traffic stream parameters in three-dimensional space with speed, flow and density representing the three different axes. Figure 6 shows the graph for speed, flow and density in three dimensions using the discrete data collected for all 2 to 1

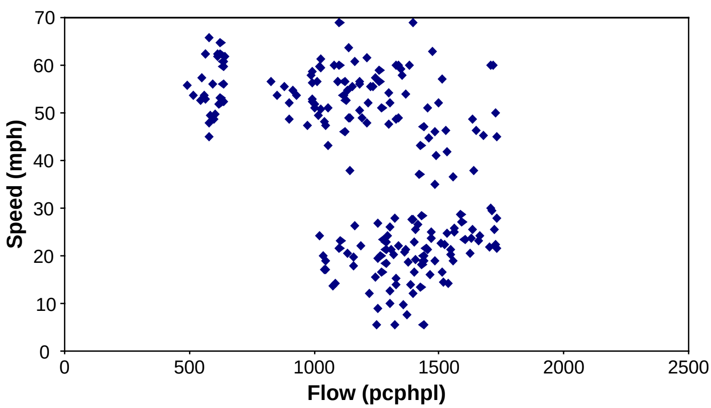

Figure 4. Graph of speed versus flow (12 consecutive five-minute periods)

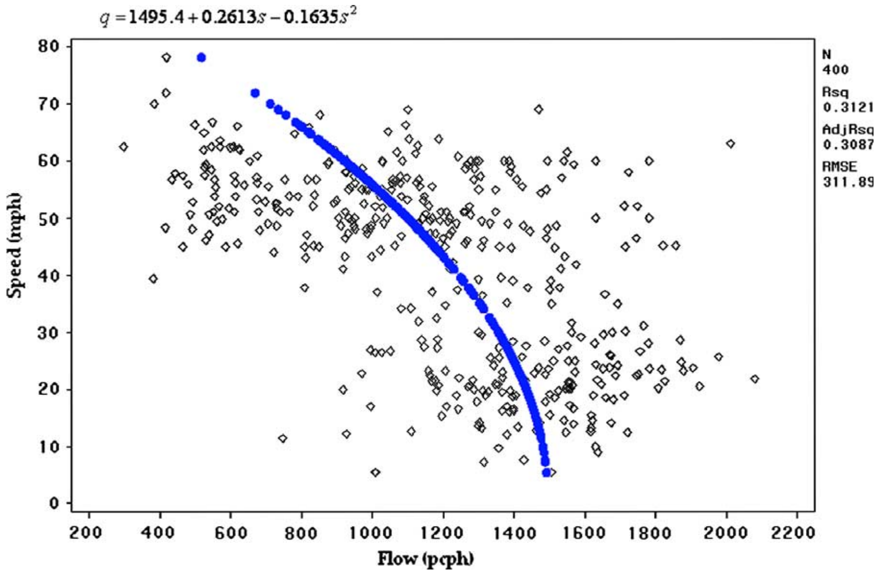

Figure 5. Two-dimensional model of speed versus flow (discrete five-minute flows)

projects. However, the three-dimensional model failed to give an exact profile of the field conditions because of the lack of data points with high speed and high density, a situation that cannot occur in the real world.

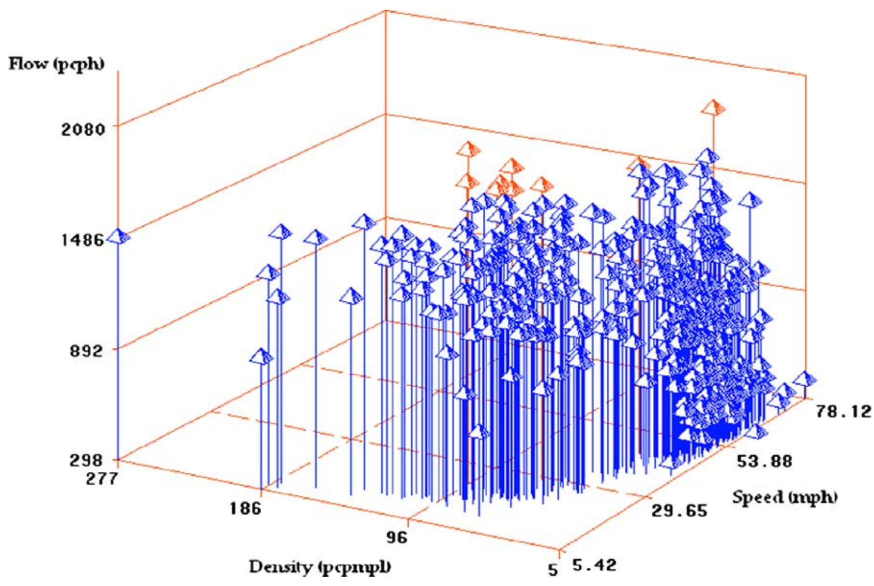

Figure 6. Three-dimensional graph of speed, flow and density (discrete five-minute flows)

Speed–density graphs. The graph of speed versus discrete density for all 2 to 1 lane closures is shown in Figure 7. The field data plotted on the graph clearly indicates that it is not following the linear trend that Greenshields' relationship defines for speed and density. Alhough the increase in density did result in a decrease in speed, the non-linear pattern relating speed and flow did not follow a straight line.

The graph in Figure 8 shows a similar non-linear pattern for the data plotted between speed and consecutive density. This graph is based on actual hourly density rather than on five-minute density projected over an hour, and the speed is the weighted average of these 12 periods. No data points were found in the region for speeds between 30 and 35 mph because none of the average speeds fall in that range.

Modeling speed and density. This research identified the non-linear pattern between speed and density, modeling it using a non-linear analysis procedure in SAS. Figure 9 presents the statistically significant model between speed and discrete density for all 2 to 1 lane projects. This model appeared to follow the shape of a hyperbola. Figure 9 also shows the non-linear equation developed between speed and discrete density. The non-linear model showed a statistically significant improvement over a Greenshields' linear model for the speed and density data.

SAS was successful in generating a model as the best fit for the field data. The partial output of the descriptive statistics provided in Figure 10 indicates that the model generated is significant, as the *P*-value was less than 0.05. The percentage error was determined using

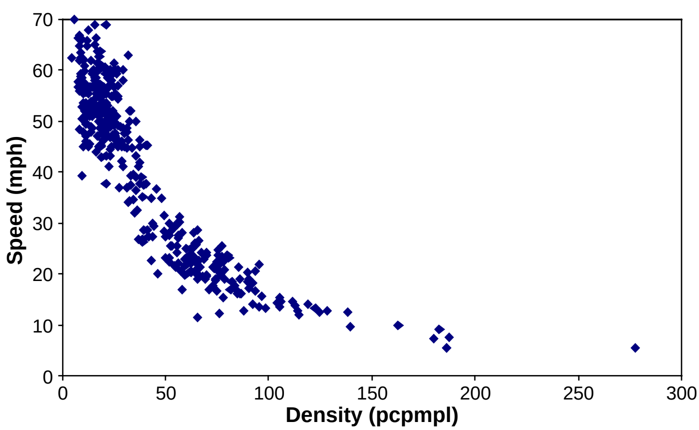

Figure 7. Graph of speed versus density (discrete five-minute flows)

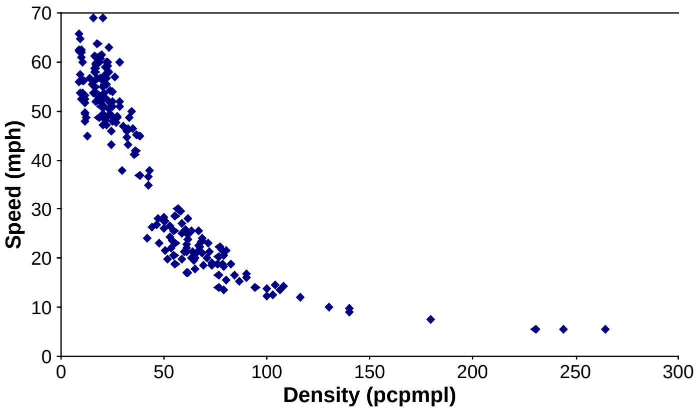

Figure 8. Graph of speed versus density (12 consecutive five-minute periods)

the proportion of the residual to the corrected total as shown in Figure 11; the results explained more than 99% of the total data with a marginal error of 0.2%.

Similarly, Figure 12 presents the model developed for 2 to 1 lane closures using consecutive densities. The generated model reflected hyperbolic structure. The model was observed to follow similar non-linear trends to those in Figure 9. Since non-linear models did not provide R^2 values, the sum of the squares of the residual and the P-value were used to determine the accuracy of the model.

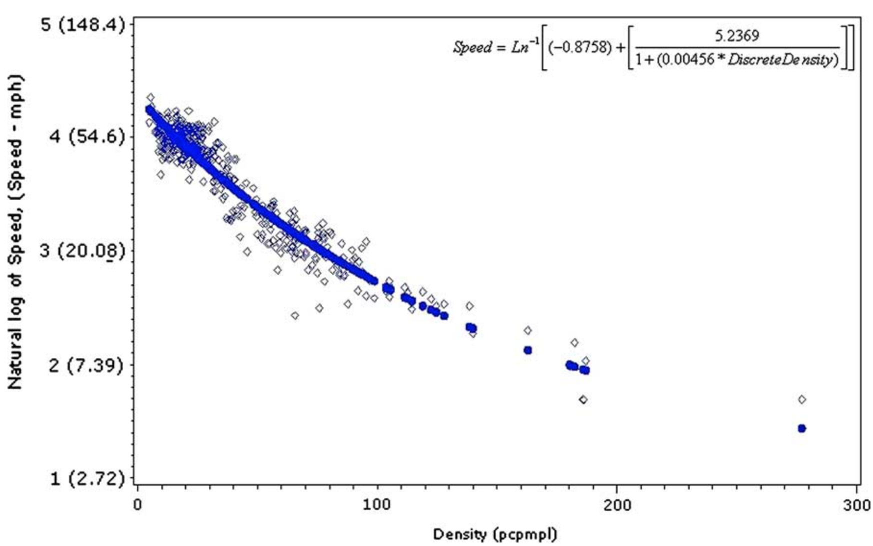

Figure 9. Model of speed versus density (discrete five-minute flows)

Estimation Summary

Method	Gauss-Newton
Iterations	7
R	2.948E-6
PPC(b1)	0.000021
RPC(b1)	0.000109
Object	1.9E-10
Objective	10.46615
Observations Read	2000
Observations Used	400
Observations Missing	1600

Source	DF	Sum of Squares	Mean Square	F Value	Approx Pr > F
Regression	3	5274.9	1758.3	1871.53	<.0001
Residual	397	10.4661	0.0264		
Corrected Total	400	5285.4			

Figure 10. Partial SAS output for speed–density model (discrete five-minute flows)

Capacity Estimation for 2 to 1 Lane Closure

The base capacity for 2 to 1 work zone lane closures was calculated using the equations generated by the speed–density models. From the general idea that flow equals velocity multiplied by density for a section of freeway, speed was substituted for flow and density in all the equations to generate capacities. The calculations for discrete conditions are shown in Figure 13. It was assumed that at capacity, the flow remains constant for a very short interval, which generates the optimum density. The base capacity was then generated by calculating the flow at optimum density.

Therefore, a value of 1550 pcphpl (rounding to the nearest 25) was applied for estimating the base capacity of a freeway work zone for the 2 to 1 lane closure configuration, based on discrete conditions that project the five-minute volumes over one hour. This estimate is similar to capacity estimates in many earlier studies on work zone capacity, such as Krammes and Lopez (1992), Jiang (1999), and Maze *et al.* (2000).

As discussed earlier, an adjustment is essential to the base PCE capacity value in order to consider trucks. *HCM* 2000 provides a procedure to determine the vehicular volume as a function of PCEs. The formulas given below were applied to the calculated base capacity, adjusting for heavy vehicles resulting in the first estimate for capacity C'.

$$\text{Percentage Error} = \frac{\text{Sum of squares of residuals}}{\text{Corrected Total}}$$

$$\text{Percentage Error} = \frac{10.4661}{5286.4} = 0.2\%$$

Figure 11. Percentage error calculation for speed–density model (discrete five-minute flows)

$$f_{HV} = \frac{1}{1 + [P_T(E_T - 1) + P_{RV}(E_{RV} - 1)]}$$

where f_{HV} = heavy vehicle adjustment factor, P_T = proportion of trucks, E_T = passenger car equivalents for trucks and buses, and E_{RV} = passenger car equivalents for recreational vehicles and cars with trailers.

$$C_B = 1550 * f_{HV}$$

where C_B = adjusted capacity for heavy vehicles with one lane open (veh/h/lane).

It was recognized that the intensity of the work zone will also have an effect on capacity. *HCM* 2000 suggests a 10% adjustment, depending on whether or not the work zone activity is more or less

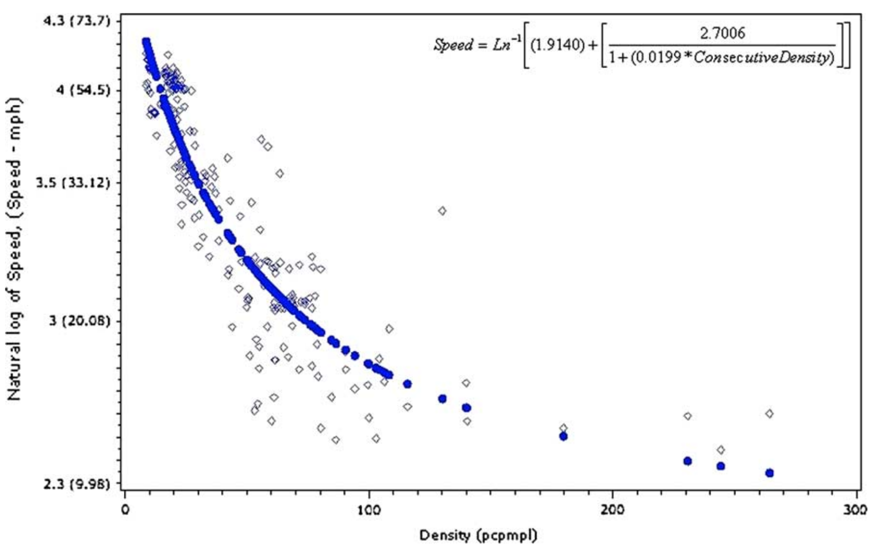

Figure 12. Model of speed versus density (12 consecutive five-minute periods)

$$s = Ln^{-1}\left[(-0.8758) + \left[\frac{5.2369}{1 + (0.00456 * k)}\right]\right]$$

$$Ln(s) = \left[(-0.8758) + \left[\frac{5.2369}{1 + (0.00456 * k)}\right]\right]$$

we know that $\mathrm{s} = \frac{\mathrm{q}}{\mathrm{k}}$; substituting in above equation

$$Ln\left(\frac{q}{k}\right) = \left[(-0.8758) + \left[\frac{5.2369}{1 + (0.00456 * k)}\right]\right] \qquad \rightarrow \mathrm{I}$$

Differenciating on both sides,

Assuming at capacity, there is no change in flow, so $\frac{\mathrm{dq}}{\mathrm{dk}} \rightarrow 0$

$$\frac{1}{\frac{q}{k}}\left[\frac{k \times \frac{dq}{dk} - q}{k^2}\right] = \left[-\frac{(5.2369 \times 0.00456)}{(1 + (0.00456 \times k^2))}\right]$$

$$\Rightarrow k^2 - 709.85k + 48091.72 = 0$$

$$\Rightarrow k = 75.86 \cong 76\, pcpmpl$$

Substituting k in equation I to get q which is base capacity,

$$\Rightarrow \mathrm{q} = 1547\, pcphpl$$

Figure 13. Base capacity calculations for discrete conditions for 2 to 1 projects

intense than normal. The final estimation for capacity is given below by C_{WZ}, which includes adjustments for intensity of work zone, heavy vehicle factor and the number of lanes open through the work zone area.

$$C_{\mathrm{WZ}} = (C_{\mathrm{B}} + I)^{*} f_{\mathrm{HV}}{}^{*} N$$

where C_{WZ} = estimated capacity of a short-term work zone (veh/h) and I = adjustment factor for type, intensity, length and location of the work activity.

Conclusions

This research collected five-minute traffic flow and velocity data in 22 work zone sites, which were maintained and operated by the South Carolina Department of Transportation (SCDOT). The visual inspection of the scatter plot of the relationship for the traffic stream parameters for 2 to 1 lane closure indicated that the relationships for speed–density were non-linear and that the relationship between speed and flow, and flow and density were not parabolic as indicated by Greenshields. Therefore, non-linear models of speed and density for both discrete five-minute data projected over an hour and continuous hourly data were developed using the Statistical Analysis Software (SAS). The speed–density model was developed for 2 to 1 lane configuration using SAS and took the form of a hyperbolic curve. Descriptive statistics indicated that there was very little deviation between the actual data and modeled estimates. It was not apparent from the literature that previous researchers have attempted to model traffic on freeways as a hyperbolic curve. While the data for this research is based only on work zones, the results suggest that it would be prudent to apply this approach to non-work zone highway traffic as well.

Based on the developed model for speed and density, the work zone capacity was determined to be 1550 pcphpl for 2 to 1 lane closure configurations. This finding is similar to values found in many previous studies on short-term work zone closures. Highway agencies can use this estimated capacity along with anticipated traffic demand to schedule work zone operations to avoid long periods of over-saturation.

The tapered approach to work zone lane closures used by SCDOT is similar to methods used in work zones throughout the world. The authors are confident that the methodology described in this paper for modeling work zone traffic as well as estimating work zone capacity is transferable to other countries. The conversion of actual volumes to PCEs may have to be modified due to the significant differences in traffic makeup between South Carolina and other countries.

The researchers postulated that factors such as terrain, work zone activity, and weather might influence work zone capacity. It was difficult, however, to examine critically the effects of these factors. The work zones studied did not reveal major differences in terrain type, nor were there sustained grades. There was insufficient data to conclude that work zone activity, intensity, and length do not affect work zone capacity. Similarly, no weather-related effects could be measured, since short-term work is generally postponed during adverse weather conditions. Additional data in a future research effort should focus on a detailed examination of all of these factors as well as different work zone lane closure configurations, such as 3 to 2 lanes and 3 to 1 lane closures.

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