Word count – 7,350 **TRB Paper Number: 06-2496**

Development of a Methodology to Estimate the Interstate Highway Capacity for Short-Term Work Zone Lane Closures

Wayne A. Sarasua
Department of Civil Engineering
Clemson University, Clemson, SC 29634-0911
Phone: (864) 656-3318, FAX (864) 656-2670
E-mail: sarasua@clemson.edu

William J. Davis
Department of Civil & Environmental Engineering
The Citadel, 171 Moultrie Street, Charleston, SC 29409
Phone: (843) 953-7686, FAX: (843) 953-6328
E-mail: jeff.davis@citadel.edu

Mashrur A. Chowdhury
Department of Civil Engineering
Clemson University, Clemson, SC 29634-0911
Phone: (864) 656-3313, FAX (864) 656-2670
E-mail: mac@clemson.edu

Jennifer H. Ogle
Department of Civil Engineering
Clemson University, Clemson, SC 29634-0911
Phone: (864) 656-0883, FAX (864) 656-2670
E-mail: Ogle@clemson.edu

November 21, 2005

ABSTRACT
Defining and understanding traffic flow parameters within short-term interstate work zones is a crucial step in developing effective policies to manage construction and maintenance work conducted on the nation's heavily traveled freeways. The South Carolina Department of Transportation (SCDOT) initiated a research study to develop a methodology for use in determining an updated lane closure policy for interstate highway work zones. Phase 1 of the research was completed in May, 2003 and findings identified threshold volumes for two-to-one lane closure work zone configurations. Phase 2 of the research further expanded numerically derived relationships and contained analysis of other short-term lane closure configurations including three-to-two and three-to-one lane closures. Both research phases concentrated on methods to determine the number of vehicles per lane per hour that can pass through short-term interstate work zone lane closure with minimum or acceptable levels of delay as defined by the SCDOT. Phase 2 includes an expanded list of data collection sites with differing work zone characteristics. This paper presents the analysis and results of Phase 2 of the research. Headway analysis revealed that passenger car equivalents (PCEs) differed for various speed ranges and modified PCE's for various speed groups were applied in calculating capacity. The authors recommended a model to be used for calculating work zone capacity that incorporates base capacity, PCEs for various speed groups, adjustment factors related to specific work zone characteristics, and number of lanes open through the work zone.

INTRODUCTION
The Manual of Traffic Control Devices Handbook (MUTCD, 2003) defines a short-term work zone as stationary daytime work that occupies a location for more than one hour within a single daylight period(1). The need to maintain adequate traffic flow through short-term interstate work zones is paramount on today's heavily traveled freeways. Numerous states have policies related to traffic flow thresholds, vehicle delay and vehicle queue lengths that provide guidance on conditions when short-term lane closures can be instituted. Generally, traffic flow threshold limits are a function of traffic stream characteristics, highway geometry, work zone location, type of construction activities and work zone configuration. The South Carolina Department of Transportation (SCDOT) initiated a research study to develop a methodology for use in determining an updated lane closure policy within work zones along the interstate highway system. The research was completed in two phases, with the second addressing research needs identified in the initial research. Both phases of this research focused on determining the number of vehicles per lane per hour that can pass through short-term, interstate work zone lane closures, with minimum or acceptable levels of delay.

Based on the original research project (Phase 1) completed in May 2003 (2), the following model was developed to describe traffic capacity in short-term work zones:

$$C_{WZ} = (1460 + I) * f_{HV} * N$$

where: C_{WZ} = is the estimated capacity of a short-term work zone (veh/hr)
f_{HV} = heavy vehicle adjustment factor
N = number of lanes open through the work zone
I = adjustment factor for type, intensity, length and location of the work activity

(Note: The initial model was based on data collected from 23 work zones with two-to-one lane closures across South Carolina.)

Based on the initial research and model development, it was determined that an 800 vehicles per hour per lane threshold, previously used by SCDOT, was low. Based on results of Phase 1 work, SCDOT increased their threshold volume to 1,000 vehicles per hour per lane for Phase 2. This provided an opportunity for more day time collection during Phase 2. Implementing a lane closure during an off-peak daytime hour would give opportunities to collect volume data that would build up gradually. Further, using a higher threshold volume would allow greater possibility to validate and possibly improve the model developed in Phase 1.

Work for this project was conducted from March 2001 to May 2005 by Clemson University, with assistance from The Citadel. The overall project goal was to determine realistic traffic flow parameters based on wide-scale, field-collected data obtained from in-state site locations and to use analytical results to revise policy threshold limits for short-term interstate work zone lane closures. Findings of Phase 1 and 2 research activities should be beneficial to motorists through reduced construction delays along the interstate highway system. Furthermore, increasing the number of work zone operations during day time hours should lead to increased construction and maintenance productivity.

BACKGROUND

The initial literature review focused on methods to measure capacity, data collection methods, and factors affecting freeway work zone capacity, in addition to providing highlights of the survey of state agencies (3). Phase 2 identified additional studies and relevant technical literature pertaining to previously established empirical relationships, current data measurement methods and factors affecting freeway work zone capacity. These sources serve to augment the original literature review and selected citations are included herein.

Review of Methods to Measure Capacity

Research by Krammes and Lopez (4) developed updated capacity values for short-term freeway work zone lane closures using data collected at 33 work zone sites in Texas between 1987 and 1991 for three to one, two to one, four to two and five to three work zone lane configurations. This study recommended a base capacity value of 1,600 passenger cars per hour per lane (pcphpl) for all short-term freeway lane closure configurations. Several adjustments were made to the base capacity value including adjustments for intensity of work activity, effect of heavy vehicles, and presence of ramps when applying to specific work zone location.

Taehyung, Lovell, and Paracha (5) developed a new methodology to estimate capacity for freeway work zones that examined various independent factors that contribute to capacity reduction in work zones. Data was collected at 12 work zone sites with lane closures on four normal lanes in one direction, mainly after the peak hour during daylight and night. A multiple regression model was developed to estimate capacity on work zones for establishing a functional relationship between work zone capacity and several key independent factors including number of closed lanes, proportion of heavy vehicles, grade, and intensity of work activity. Model results were compared with existing capacity models using the root mean square (RMS) error, and showed the new capacity estimation model is better than the others, which exclude key independent factors affecting work zone capacity.

An investigation conducted in Ontario, Canada by Al-Kaisy and Hall (6) on freeway capacity at several reconstruction zones focused on estimating freeway capacity at reconstruction sites. Individual investigations were used to estimate a base capacity for freeway reconstruction sites and determine the effect of important factors including heavy vehicles, driver population, rain, site configuration, and work zone activity. A generic work zone capacity model was created for freeway reconstruction sites using a base capacity value of 2,000 passenger cars per hour per lane for reconstruction sites under favorable conditions with heavy vehicles and driver population exhibiting the effect on capacity.

Adeli (7) conducted a study to model work zone capacity using a case-based reasoning model for freeway work zone traffic management that considered work zone layout, traffic demand, work characteristics, traffic control measures, and mobility impacts. An adaptive computational model was created for estimating work zone capacity, queue length and delay.

Benekohal, Kaja-Mohideen, and Chitturi (8) presented a methodology for estimating speed and capacity in freeway work zones. The underlying principle of this methodology is that operating factors in work zones, which include work intensity, lane width, lateral clearance, and other factors, cause motorists to reduce their speed. Video data was collected for 11 two-to-one work zone lane closures on interstates in Illinois including eight long-term and three short-term sites. Work zone intensity was quantified and correlated with consequent speed reduction using field data for long-term work zones and driver survey data for short-term work zones. Based on these relationships an anticipated work zone operating speed can be computed using a speed-flow relationship developed from project data.

Chitturi, and Benekohal (9, 10) 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. Findings indicate none of the programs produced results that were reasonably close to observed field data. This study also found that predicting speed reductions should be a function of vehicle size and not be a constant value for all vehicle classifications.

A study by Dixon et al. estimated work zone capacity values for rural and urban freeways in North Carolina This study found that intensity of work zone activity and type of study site, i.e., rural or urban, had strong affects on work zone capacity (11). This study found that for two to one lane operation in rural sites with heavy work intensity, capacity was 1210 vehicles per hour per lane in the activity area, where as in urban area with same lane operations under moderate and heavy work zone intensity, activity area capacity were 1560 vehicles per hour per lane and 1490 vehicles per hour lane, respectively. This study reported an activity area capacity of 1440 vehicles per hour per lane for moderate work intensity in urban sites.

DATA COLLECTION

Data collection on this project was accomplished through use of video surveillance cameras, radar speed detection, and manual queue length measurement at 23 work zone sites for Phase 1 and 12 additional sites for Phase 2. The sites included a variety of short-term lane closure conditions located along interstate routes throughout the state of South Carolina. A log of all 34 site locations showing time, location, type of work, closure geometry, taper length and other descriptive information is summarized in Table 1. Summary statistics for the 21 data collection sites is presented in Table 2. This table includes information on traffic stream characteristics, volumes, passenger car equivalents and vehicle queue conditions. Truck percentages for work zone locations included in the study ranged from a high of 40 percent to a low of 3 percent, with an average for all sites of just over 21 percent. Thirteen of the sites (including most of the sites collected during phase 2) experienced vehicle queues extending beyond one mile in length, while twelve of the sites did not experience measurable vehicle queue lengths.

TRB 2006 Annual Meeting CD-ROM

Table 1 (a) - Log of Initial Data Collection Locations: Phase 1

Work Zone Project Log												
Site #	Date	Time		Location			Type of Work	Closure Geometry	Taper Length	Equipment Activity	Length of Work Zone	Weather Conditions
		Start	End	Interstate	Direction	MPM						
1	09/12/01	19:15	21:15	85	N	32	Median Cable Guardrail	Inside lane of 2 closed	863	light	short	Warm, Clear
2	09/13/01	19:45	20:45	26	W	54	Median Cable Guardrail	Inside lane of 2 closed	795	light	short	Warm, Clear
3	09/16/01	19:40	21:15	85	S	8.5	Median Cable Guardrail	Inside lane of 2 closed	600	light	short	Warm, Clear
4	09/30/01	19:05	22:30	85	N	0	Median Cable Guardrail	Inside lane of 2 closed	665	light	short	Warm, Clear
5	10/01/01	9:00	18:00	77	N	80	Paving (OGFC)	Inside 2 lanes of 4 closed	675, 1475, 850	heavy	long	Warm, Clear
6	10/03/01	17:00	22:30	385	N	40	Paving (surface)	Outside lane of 2 closed	446	heavy	long	Warm, Clear
7	11/05/01	20:00	22:00	26	W	208	Final striping	Outside 2 lanes of 3 closed	668, 1544, 684	heavy	short	Cold, Clear
8	01/31/02	15:30	16:00	26	E	178	Conc Pvmt Repair	Outside lane of 2 closed	800	heavy	medium	Cool, Clear
9	03/11/02	16:00	18:10	385	W	2	Median Cable Guardrail	Inside lane of 2 closed	950	light	long	Cool, Clear
10	04/03/02	8:30	10:30	26	E	104	Median Cleanup	Inside lane of 3 closed	-	light	short	Warm, Clear
11	04/08/02	8:42	11:10	26	E	107	Median Cleanup	Inside lane of 4 closed	575	light	short	Warm, Clear
12	06/03/02	19:00	21:15	85	S	28	Paving	inside lane 1of 3 closed	800	light		clear
13	06/04/02	19:00	20:30	85	S	28	Rumble Strips	Inside lane 1 of 3 closed	-	light		clear
14	06/06/02	19:00	19:00	85	S	28		Inside lane 2 of 3 closed	800	light		clear
15	06/07/02			85	S		data collection cancelled due to weather conditions,after completion of equipment set -up					Rain
16	06/13/02	19:00	21:00	85	S	28		Inside 1 lanes of 3 closed		heavy		Warm, Clear
17	06/14/02	19:00	21:20	85	S	28	Concrete Paving	Outside lane of 2 closed	-	heavy	long	Warm, Clear
18	06/20/02	20:00	22:00	85	S	28	Concrete Paving	Outside lane of 2 closed	800	heavy	long	Warm, Clear
19	07/09/02	19:15	20:15	85	S	2	Bridge Maintenance	Outside lane of 2 closed		light	long	Warm, Clear
20	07/21/02	19:03	21:08	85	N	179	Bridge Maintenance	Outside lane of 2 closed		light	long	Warm, Clear
21	07/22/02	18:56	20:30	85	N	179	Bridge Decil Maintenance	Outside lane of 2 closed		light	long	clear
22	08/23/02	21:00	22:00	26	W		Concrete Paving	Outside 2 lanes of 3 closed	800	light	long	clear
23	08/14/02	19:17	21:00	95	N	165	Barrier Wall Erection	Inside 1lane of 2 closed	800	light	long	clear

Paper revised from original submittal.

TRB 2006 Annual Meeting CD-ROM

Table1 (b) -Log of New Data Collection Locations: Phase 2

Work Zone Project Log												
Site #	Date	Time		Location			Type of Work	Closure Geometry	Taper Length	Equipment Activity	Length of Work Zone	Weather Conditions
		Start	End	Interstate	Direction	MPM						
24	10/14/03	21:00	23:35	85	S	54	Milling	Inside 2 lanes of 3 closed		heavy	long	Clear
25	03/12/04	20:15		85	S	54	Paving	Inside 2 lanes of 3 closed	800, 1200, 800	heavy	long	Clear
26	03/17/04	21:35	0:11	85	N	54	Milling	Inside 2 lanes of 3 closed		heavy	long	Clear
27	05/13/04	20:40	22:35	77	N		Bridge Widening	Outside 1 lane of 3 closed	800	light	medium	Warm, Clear
28	05/13/04	16:15	18:15	77	S		Bridge Widening	Outside lane 1 of 3 closed	750	light	medium	Warm, Clear
29	05/14/04	16:10	18:25	77	S		Bridge Widening	Outside lane 1 of 3 closed	750	light	medium	Warm, Clear
30	05/14/04	6:52	8:25	77	N		Bridge Widening	Outside 1 lane of 3 closed	800	light	medium	Warm, Clear
31	06/24/04	19:00	19:00	20	W		Paving	RAINED OUT				Rain
32	07/09/04	21:25	22:10	20	W		Paving	Outside 2 lanes of 3 closed		heavy	long	Clear
33	10/12/04	7:15	9:00	26	E	76	Milling	Outside lane of 2 closed	800	light	short	Warm, Clear
34	10/20/04	20:50	23:30	85	S	54	Paving	Inside 2 lanes of 3 closed	800	heavy	long	Warm, Clear
35	12/13/04			20		70	Paving	Inside 2 lanes of 3 closed	800	heavy	medium	Clear

Paper revised from original submittal.

TRB 2006 Annual Meeting CD-ROM

Paper revised from original submittal.

Table 2 (a) - Summary of Initial Traffic Flow and Vehicle Queue Conditions at Work Zone Sites: Phase 1

Site #	Location	PC%	T%	Vehicles						Passenger Car Equivalents						Queue?	Max Queue Length
				1 min Hourly Volume		5 min Hourly Volume		Hourly Volume		1min Hourly Volume		5 min Hourly Volume		Hourly Volume			
				max	min	max	min	max	min	max	min	max	min	max	min		
1	I-85 N MPM32	64.33%	35.67%	1980	60	1056	648	-		3060	60	1560	1044	-		none	-
2	I-26 W MPM 54	71.05%	28.95%	1320	120	648	324	497	445	1680	180	882	492	702	640	none	-
3	I-85 S MPM 8.5	87.25%	12.75%	2160	300	1572	636	1221	767	2700	300	1824	726	1414	918	few	3200
4	I-85 N MPM 0	82.63%	17.37%	2100	120	1440	324	1320	995	2280	120	1728	534	1540	1243	continuous	>1 mile
5	I-77 N MPM 80	84.56%	15.44%	1410	450	1140	636	930	802	1770	555	1389	765	1112	954	none	-
6	I-385 N MPM 40	96.83%	3.17%	1140	120	744	60	553	458	1500	120	768	60	572	479	none	-
7	I-26 W MPM208	87.62%	12.38%	1800	360	1308	576	1124	735	2160	360	1506	666	1310	871	none	-
8	I-26 E MPM 178	84.45%	15.55%	1680	360	1128	720	927	871	2010	450	1416	864	1107	1059	none	-
9	I-385 N MPM 2	84.49%	15.51%	1320	0	696	276	565	509	1710	0	918	312	689	608	none	-
10	I-26 E MPM 104	88.68%	11.32%	2280	1140	2016	1266	1041	1041	2565	1245	2262	1446	1178	1178	continuous	>4500
11	I-26 E MPM 107	91.06%	8.94%	1722	678	1480	1044	1308	1152	1968	738	1620	1152	1437	1284	none	-
12	I-85 S MPM 28	68.61%	31.39%	1740	180	1284	636	1090	820	2520	180	1758	1056	1518	1217	none	-
13	I-85 S MPM 28	72.68%	27.32%	2220	180	1668	756	1251	976	3510	270	2232	960	1640	1428	Discontinuous	500
14	I-85 S MPM 28	73.69%	26.31%	2100	480	1524	1008	1357	1141	2790	660	2202	1428	1836	1574	Discontinuous	8000
16	I-85 S MPM 28	73.42%	26.58%	2160	540	1500	936	1341	1047	2790	210	2100	1296	1844	1441	Discontinuous	>1 mile
17	I-85 S MPM 28	82.79%	17.21%	2280	120	1680	660	1504	1240	2640	120	2070	768	1793	1564	continuous	>1 mile
18	I-85 S MPM 28	69.67%	30.33%	1800	360	1452	732	1110	916	2550	450	1998	1056	1552	1331	continuous	3000
19	I -85 S MPM 02	66.93%	33.07%	1800	240	1236	636	672	672	2070	330	1674	930	995	995	none	-
20	I -85 N MPM 179	85.96%	14.04%	1980	120	1032	648	903	799	2670	210	1500	978	1332	1198	continuous	>1mile
21	I -85 N MPM 179	65.57%	34.43%	1800	300	1548	384	1339	867	2190	360	1830	558	1536	1065	none	-
22	I -26 W	90.40%	9.60%	2100	420	1104	948	920	131	2550	420	1338	1110	1038	149	Discontinuous	
23	I-95 N MPM165	69.35%	30.65%	1380	300	1032	648	907	815	2130	390	1500	924	1276	1179	Discontinuous	5000
Average		79.18%	20.82%	1831	316	1286	659	1042	819	2355	351	1640	869	1306	1065		

TRB 2006 Annual Meeting CD-ROM

Table 2 (b) - Summary of New Traffic Flow and Vehicle Queue Conditions at Work Zone Sites: Phase 2

Site #	Location	PC%	T%	Vehicles						Passenger Car Equivalents						Queue?	Max Queue Length
				1 min Hourly Volume		5 min Hourly Volume		Hourly Volume		1min Hourly Volume		5 min Hourly Volume		Hourly Volume			
				max	min	max	min	max	min	max	min	max	min	max	min		
24	I-85 S MPM 54	63.61%	36.39%	1380	60	1068	540	916	712	2054	60	1650	870	1407	1131	continuous	3300
25	I-85 S MPM 54	68.30%	31.70%	1380	60	1176	540	899	838	1997	148	1564	752	1347	1201	continuous	4100
26	I-85 N MPM 54	59.31%	40.69%	1440	360	1188	504	860	639	2130	450	1734	714	1224	1092	continuous	5033
27	I-77 N	85.41%	14.59%	2010	540	1734	726	1600	1083	2256	714	1945	943	1816	1324	none	-
28	I-77 S	82.58%	17.42%	2040	0	1596	936	1380	1221	2652	0	2002	1165	1712	1475	continuous	5000
29	I-77 S	85.92%	14.08%	1980	1020	1824	1224	1533	1356	2508	1134	2124	1423	1795	1594	continuous	4000
30	I-77 N	77.94%	22.06%	1920	420	1572	852	1394	1237	2214	510	1912	1099	1786	1575	continuous	4167
31	I-20 W - RAINED OUT																
32	I-20 W	85.97%	14.03%	2100	960	1836	1224	1609	1343	2567	1048	2141	1423	1905	1578	continuous	3800
33	I-26 E MPM 76	85.11%	14.89%	1620	180	1464	660	1068	858	1950	180	1644	846	1268	1047	discontinuo	3500
34	I-85 S MPM 54	85.97%	14.03%	2100	960	1836	1224	1609	1343	2520	1050	2130	1428	1902	1587	continuous	4000
Average		78.01%	21.99%	1797	456	1529	843	1287	1063	2285	529	1885	1066	1616	1360		

Paper revised from original submittal.

DATA ANALYSIS

Analysis of work zone data comprehensively reveals the relationship between speed and flow rate appears to follow a multi-regime distribution proposed for freeways in references such as the 2000 Highway Capacity Manual (12). Traffic characteristics of freeway work zones were analyzed using classic methods of macroscopic traffic flow modeling. Relationships between speed, density, flow, and time headway were derived using an assumed linear relationship between density and speed. Phase 1 work zone data generally supported this assumption, which was originally proposed by Greenshields (13). After combining Phase 2 data with the original data from Phase 1, the statistical goodness of fit of the data set to a Greenshields parabola was not very apparent. This finding further served to support more recent literature suggesting a multi-regime distribution. Development of model improvements and associated data analysis enhancements for estimating work zone capacity conducted in Phase 1 are presented in the following paragraphs.

On this project, a process for estimating work zone traffic flow (*q)* at capacity similar to that followed by Greenshields was thought to be an appropriate methodology as a starting point, assuming collected data would exhibit a sufficient distribution of headway values ranging from light to congested traffic conditions. Ideally, data collection at a single location would include a series of points that fall in all three traffic flow zones; uncongested flow, congested flow and queue discharge. In all 35 data collection projects in this research, only Projects 27, 28 and 29, located on I-77 in Columbia, had traffic flow data characteristic of the all three Greenshields traffic zones. Many of the hourly volumes for other projects remained well below capacity throughout the entire duration of the data collection process. On still other projects, queues formed instantaneously and grew at a significant rate indicating the approach volume, when the work zone was initiated, was considerably higher than the available capacity through the work zone. In an effort to improve the range of data used for analysis, it was necessary to combine data from similar projects. Figure 1 shows a graph of speed versus density for all two-to-one lane closure projects collected during project Phases 1 and 2. Data distribution shown on the graph follows Greenshields classic linear relationship where an increase in density results in a corresponding decrease in speed. No single project exhibits data that follows the entire range of the trend line. Figure 1 illustrates the need to use combined data to numerically define work zone capacity and related traffic flow parameters.

The drawback of combining projects is that it is difficult to isolate characteristics of individual projects that might influence capacity. Thus, an underlying assumption had to be made that all combined projects were homogeneous. In most cases, projects shared some commonality. All projects had 12-ft lanes and similar taper lengths. Rolling terrain was common to most of projects except for flat sections of I-26 east of Columbia. The primary differences in the work zone projects were type of activity and the length of the work zone. Further, project data shown in Figure 1 indicates most two-to-one lane closure projects follow the same trend, further supporting the hypothesis that a great deal of commonality exists between operational characteristics of the various project locations. In the initial data analysis, the only stratification used to separate projects was in terms of number of lanes downstream. Thus, all of two-to-one lane closure projects were separated from three-to-two and three-to-one lane closure. Additional data collected in Phase 2 has been used to quantify differences in capacity for these three lane closure geometries included in the study.

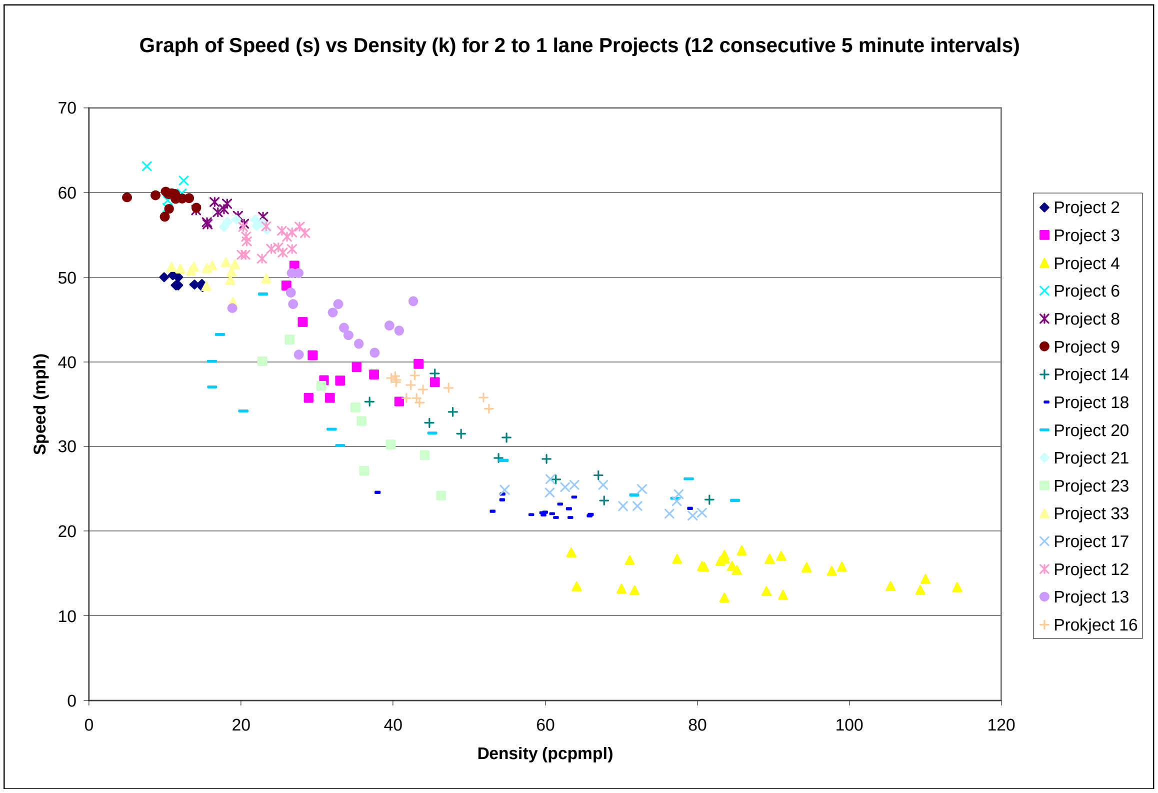


Figure 1 - Graph of Speed (*s*) Versus Flow (*q*) for 2-to-1 lane Project Sites
(12 consecutive 5-minute periods)

Considering Heavy Vehicles

The variability of truck usage on South Carolina's interstate makes it necessary to consider the affect of trucks on work zone traffic flow. To address this important issue, a procedure was used to estimate a passenger car equivalence (PCE) value for trucks and recreational vehicles (RVs) by measuring headways. As a part of this project work plan, Narapsetty (14) investigated PCE variability using data collected from the 35 work zone sites. A key finding was that passenger car equivalencies are indirectly proportional to speed up to a bracketed threshold speed. PCE values were calculated for the following ranges:

- Less than 15 MPH, PCE for trucks = 2.47
- 15 to 30 MPH, PCE for trucks = 2.22
- 30 to 45 MPH, PCE for trucks = 1.90
- 45 to 60 MPH, PCE for trucks = 1.90

Observed differences in PCE values are primarily due to acceleration and deceleration characteristics of trucks and are further explained by understanding that for speeds less than 30 mph, vehicles are likely traveling in a forced flow state where acceleration and deceleration is cyclically surging within the traffic stream. Figure 2 shows speed-flow relationships in PCEs for two-to-one lane closures (discrete 5 minute flows) using variable PCE truck values superimposed with data using a fixed 1.9 PCE truck values, calculated from data collected in Phase 1 of the project. The figure illustrates a noticeable shift in per lane flow for speeds less than 30 mph. It should be noted that the 2000 Highway Capacity Manual (HCM (12) does not account for variable PCE values. While the selection of PCE values does not affect capacity estimates for under- saturated flow conditions occurring at speeds of greater than 30 MPH, over saturated conditions occurring at less than 30 MPH are adversely affected and corresponding higher PCE values increase the time required for vehicle queues to dissipate.

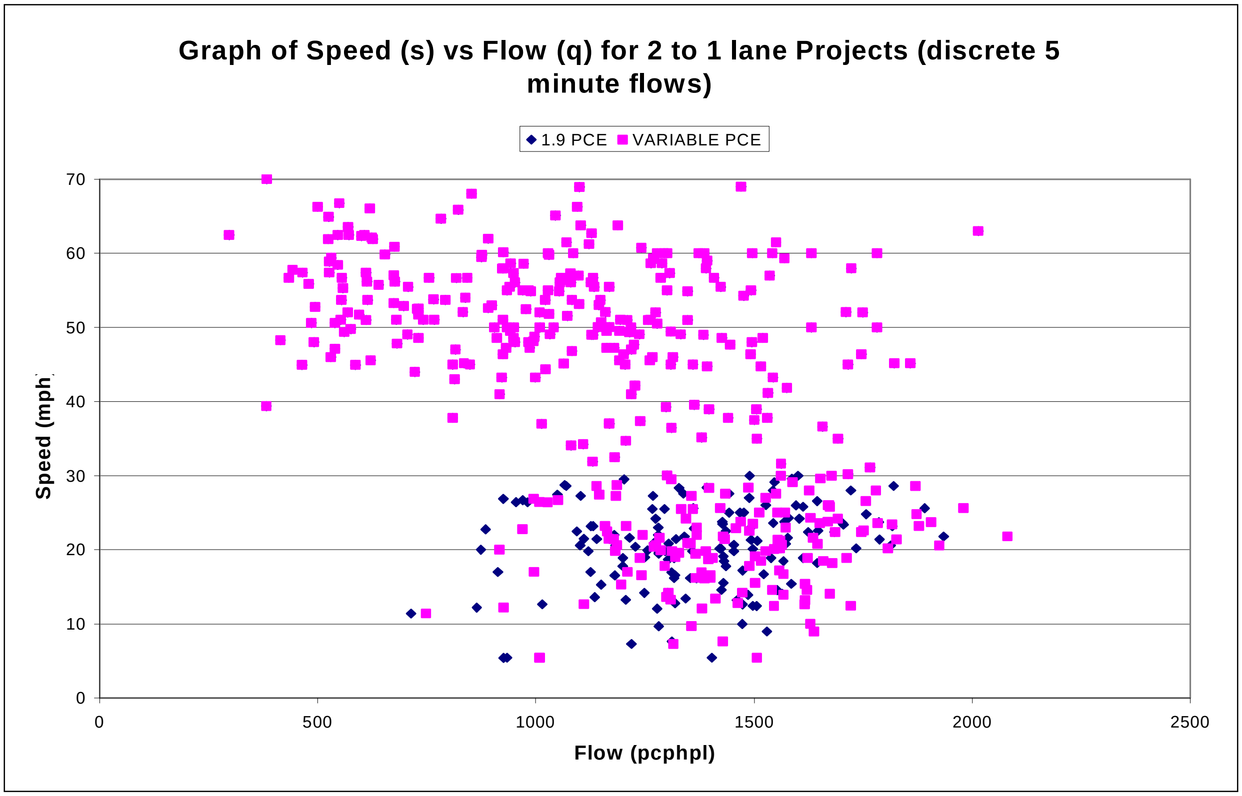


Figure 2 - Graph of Speed (*s*) Versus Flow (*q*) for 2 to 1-lane Project Sites
(discrete 5 minute flows using fixed and variable PCEs)

Formulating a Model to Estimate Work Zone Capacity

With an expanded database from 23 to 34 work zone sites, the previous speed, density and flow relationships using Greenshields' are revised and serve to define a linear relationship between speed and density. Using the PCE flow data, and speed data from this project, the corresponding densities can be estimated by the equation $k=q/s$, where: k = density (veh/mi), q = flow (veh/hr), and s = speed (mph). The resulting graph of speed versus density data is presented in Figure 3, for 2 to 1-lane work zones using 5-minute discrete data. A linear relationship is clearly evident. Using linear regression, an equation was established with a R^2 value of 0.73, which indicates the data does not fit the model particularly well. Based on review of data distribution, it is observed that instead of a linear relationship between speed and density, it appears as if there is a nonlinear trend that is asymptotic about the x-axis (speed approaches but never reaches 0 as density increases. However, continuing with Greenshields' approach by substituting into the density-flow-speed equation and solving for q produces the following numeric relationship for estimating traffic flow in two-to-one lane closures for interstate work zone areas:

$$q= -2.447\, s^2 + 140.920\, s \qquad \text{(based on 5-minute discrete data)}$$

where: q = flow (pcphpl) and, s = speed (mph)

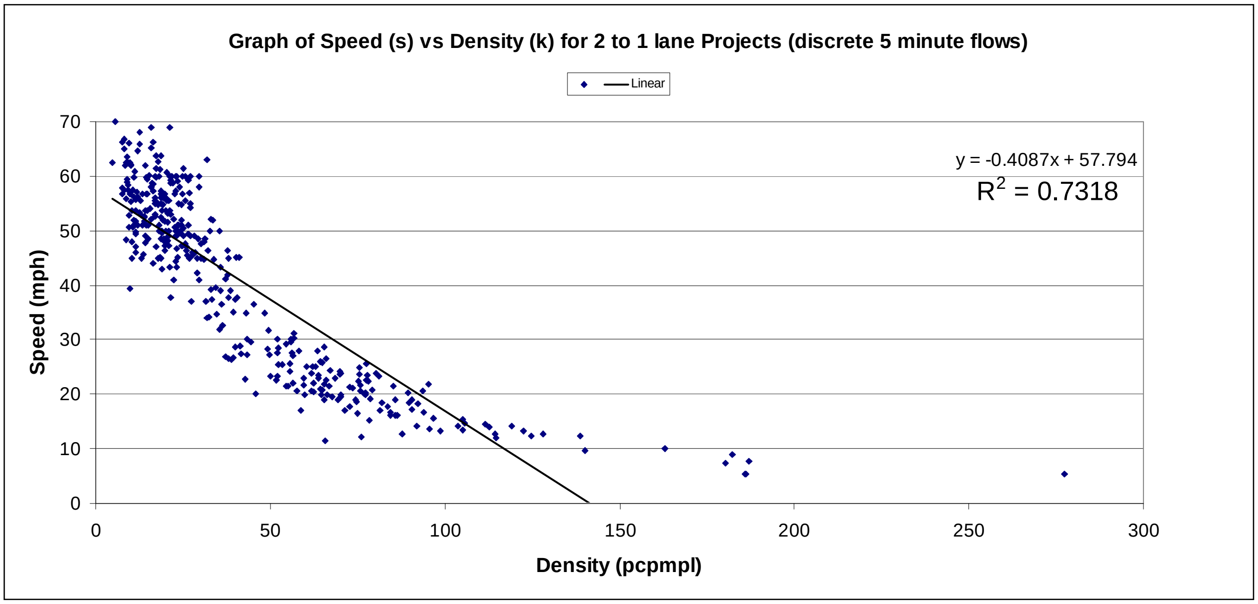


Figure 3 - Graph of Speed (*s*) Versus Density (*k*) for 2 to 1-lane Project Sites
(discrete 5-minute flows)

Figure 4 presents a graph of the two-to-one lane closure data superimposed with the modeled Greenshields parabola. As expected based on the fit of the speed-density models, the parabolic model predicting the speed-flow relationship does not fit the data well. Estimated capacity is represented on the parabolic model as the point of maximum flow where the parabola inverts. Modeled capacity appears higher than the actual capacity represented by the data distribution. Recent literature supports the observation that a Greenshields parabolic form differs from empirical data, and further suggests data is best represented by a multi-regime distribution, as previously discussed. Two regimes are clearly indicated in the project data plots; one when traffic is operating at, or below, capacity; and another when traffic is operating over capacity. The transition between these two regimes occurs very abrupt for all data collection sites.

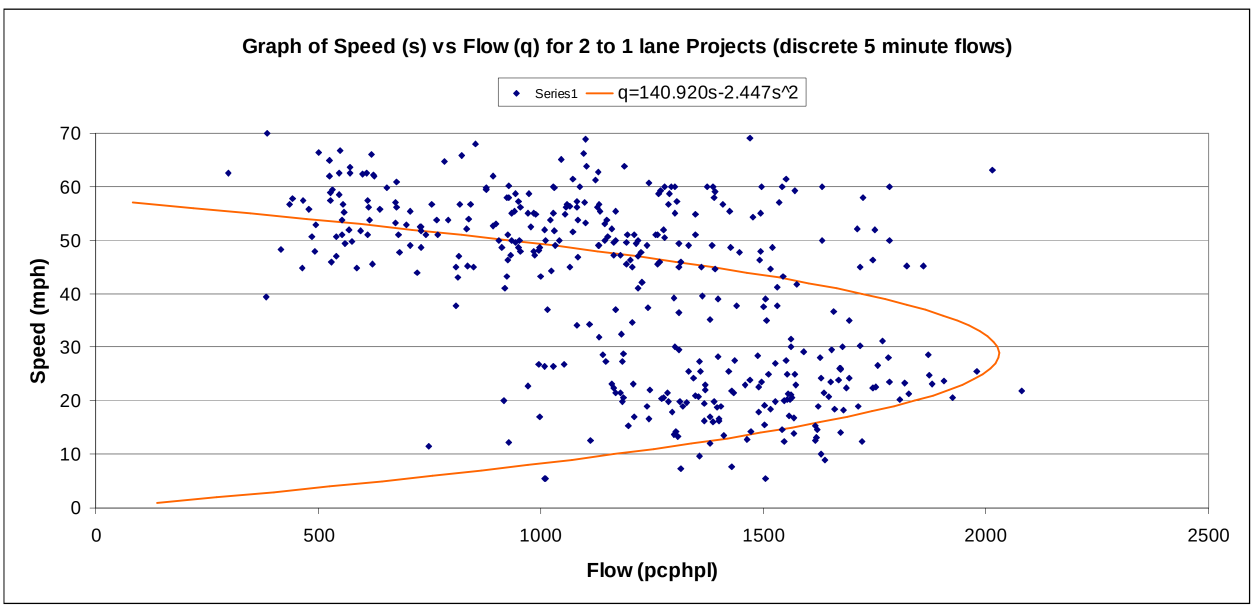


Figure 4 - Graph of Speed (*s*) Versus Flow (*q*) for 2 to 1-lane Project Sites
(Model is superimposed with discrete 5-minute flows)

An Alternative Approach to Estimate Capacity

With the addition of Phase 2 data collection sites, it became evident that the relatively poor fit of the speed-density data linearly suggests the Greenshields modeling approach to estimating capacity is not as reliable as desired. To address this problem an alternative approach was developed based on cumulative density graphs of data greater than 30 MPH representing traffic flows occurring at or below capacity. Data plots for differing lane closure configurations are provided in Figure 5 and were used to identify a reasonably conservative estimate of capacity. It should be noted the data follows characteristic curves of cumulative density graphs. The 85th percentile value was chosen as an appropriate estimate of capacity because of its extensive use as a threshold in transportation and other statistical applications. The usefulness in choosing a specified percentile for estimating capacity is that this approach provides a cushion or margin of safety, to prevent normal traffic variation from creating capacity problems as flow approaches the threshold volume is reached. Further review of the graphs indicate the 85th percentile graph produces a conservative estimate of capacity because the data maintains a linear distribution beyond the 85th percentile prior to abruptly curving upward above the 95th percentile, indicating unstable traffic flow conditions. 85th percentile passenger car volumes taken from the graphs in Figure 5 are summarized as follows:

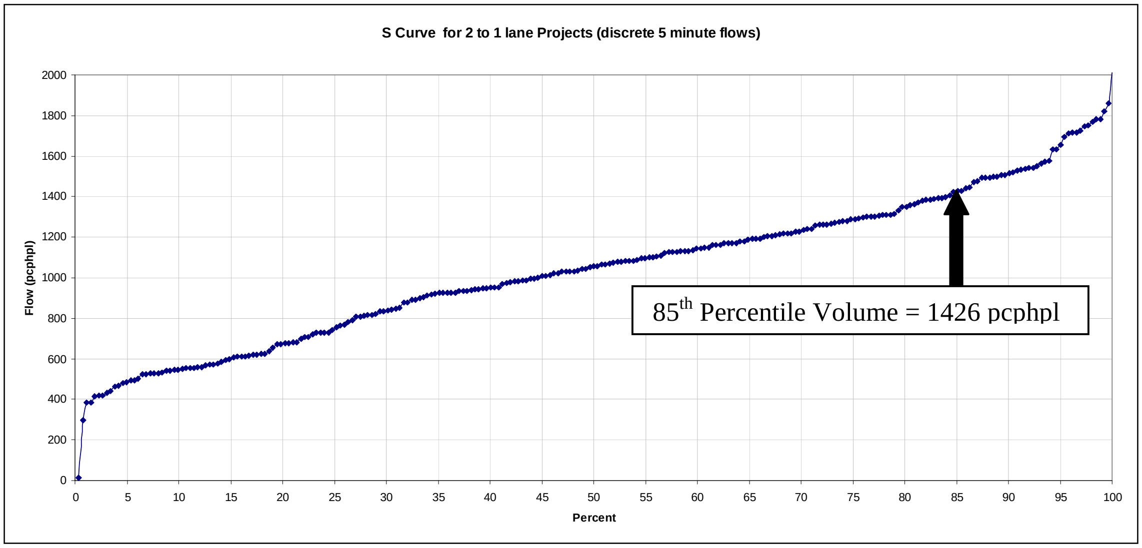
- Two-to-one lane closures = 1,426 passenger car per hour per lane
- Three-to-one lane closures = 1,280 passenger car per hour per lane
- Three-to-two lane closures = 1,791 passenger car per hour per lane

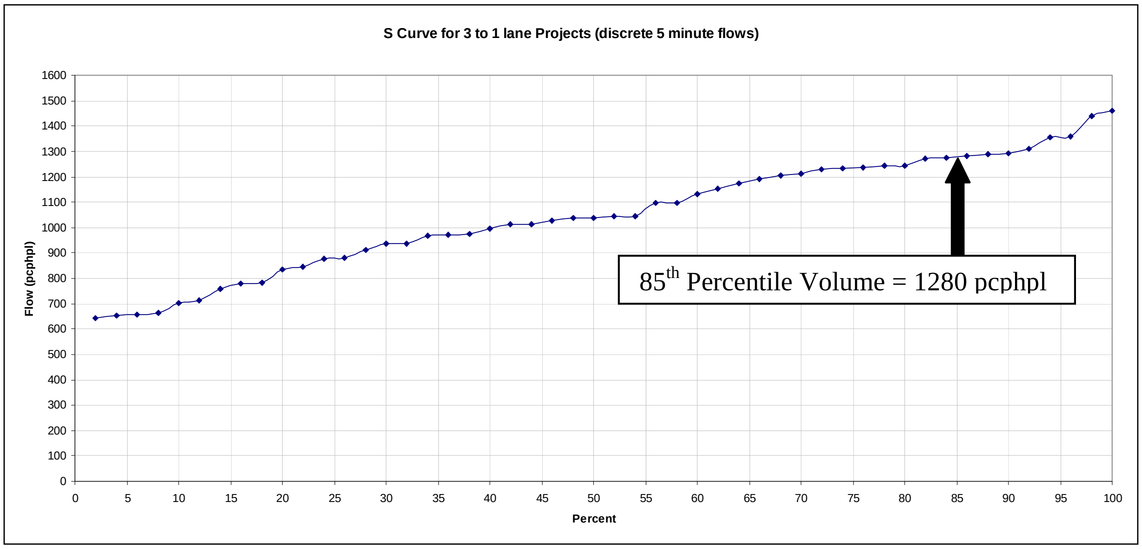
Some interesting observations are evident in the data distribution and corresponding determination of capacity threshold volumes. In the case of a three-to-one lane closure the 85th percentile volume (1,280 pcphpl) is approximately 150 vehicles less than for projects with a two-to-one lane closure (1,426 pcphpl). A likely explanation of this difference is due to the presence of additional upstream traffic flow turbulence associated with a double lane closure, resulting in predictable reduced per lane capacity values.

Another interesting finding from the data plots is the capacity estimate for three-to-two lane closure of 1,791 pcphpl which is 365 vehicles greater than two-to-one and 511 vehicles greater than three-to-one lane closures indicating that when two lanes are maintained through the work zone per lane capacity is more than doubled over what a single lane can accommodate. This occurrence is readily explained by the fact that the influence of individual vehicles on capacity is diminished when an additional lane is available. For example, in cases when a single lane is available, a slow moving vehicle will adversely impact the speed of proceeding vehicles following in a platoon. When two lanes are available, slow moving vehicles can be passed within the work zone area which reduces the negative influence of trucks and results in increased per lane capacities.

Consideration of Related Factors

An initial objective of the research was to estimate capacity by considering factors such as grade, lane width, and work zone type. By stratifying data based on the factors affecting capacity, other graphs can be created and the maximum capacities and 85th percentile volumes can be identified and compared to those using all combined data. An inherent problem is that stratifying data results in creation of models with fewer data points than desired. Regardless of this limitation, several issues related to other important factors are discussed in the following subsections.





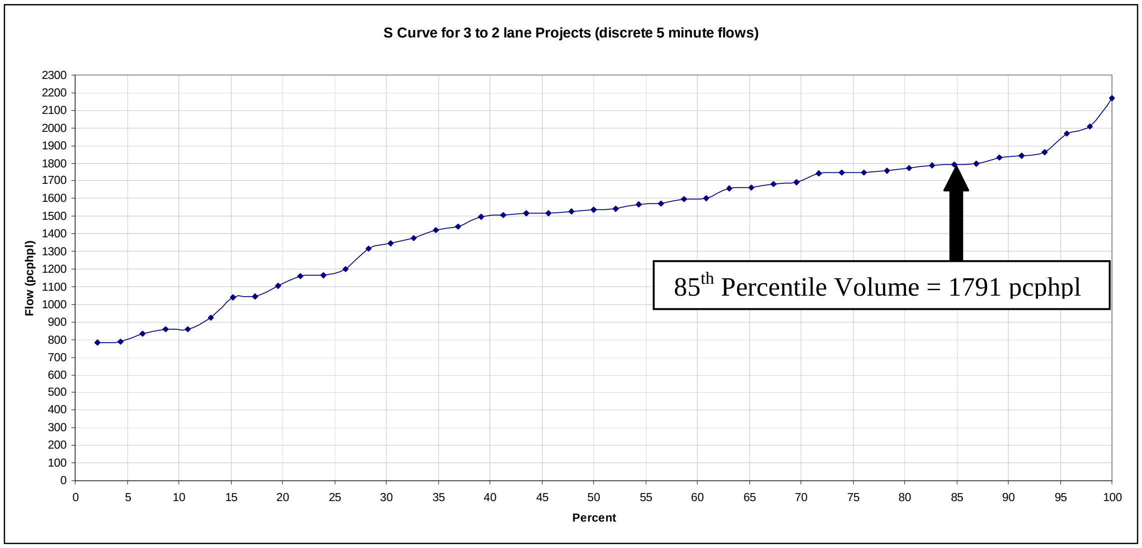


Figure 5 – Cumulative Density Graphs

Roadway Grades

All work zone locations used in this study exhibited rolling terrain and were well within typical design parameters for interstate freeways–e.g. moderate grades not extending more than one-half miles in length. Only one of the project sites could be considered a flat section and none of the sites existed along a continuous grade. Therefore, stratifying data by roadway grade was not feasible. Additionally, grouping work zone site data according to region did not indicate noticeable difference in estimated capacity. For example, two-to-one lane closures on Interstate 85 were compared to similar lane closures on all other interstates. Scatter plots of speed versus density followed nearly identical trends and the 85th percentile volumes were roughly the same. Further, the overall cumulative density functions were comparable. With regard to PCE's, the analysis indicates that PCE values identified in this study for trucks correlated closely with the PCE's for trucks on rolling terrain as identified in the 2000 Highway Capacity Manual (10) for basic freeway segments. It stands to reason that HCM values for specific freeway grades are also applicable to work zones, as well.

Work Zone Activity

The initial regression model created from the combined database was modified using dummy variables for work zone type, work zone intensity, and work zone length. A value of one was assigned to a work zone with a high degree of activity and a value of zero coded otherwise. Similarly, a value of one was assigned to a longer work zone and a value of zero coded otherwise. Stepwise regression was used to analyze the individual effect of each dummy variable. Results from the procedure indicate no significance for either of these variables. This finding was not surprising in that most work zones with heavy activity did not have a sufficient range of volume to indicate the activity or length affected work zone capacity, even with a higher threshold value of 1,000 vph currently in use. Clearly, this research does not contain sufficient data to conclude the effect of work zone activity, intensity, and length on capacity.

One observation that was made during the data collection is that the variable positioning of lane closure barricades can considerably influence work zone speed. At data collection site, a few barricades straddled a lane, forcing drivers to encroach on a narrow shoulder in the vicinity of guardrail causing drivers to slow significantly for a short period before speeding up once they were clear of the barricades.

Weather Conditions

Adverse weather was never experienced at any of project sites. SC DOT's policy avoids short-term lane closures in times of adverse weather. Several projects were cancelled and in most cases rescheduled if weather was a factor. Thus, weather was not considered in the model.

Final Form of Short-Term Work Zone Capacity Model

Model formulation identified a capacity in passenger car equivalents as 1,426 pcphpl for a 1-hour period for a two-to-one lane closure. This is only 34 fewer pcphpl that the capacity identified in the Phase 1 research. A value of 1,425 (rounding to the nearest 25) was considered a starting point for estimating work zone capacity for the boundary conditions identified in Phase 2. As per Highway Capacity Manual procedures, use of a heavy vehicle adjustment is necessary to determine a realistic PCE value. Additionally, a variable for number of lanes should also be included to address multi-lane work zone capacities. Adding a variable for heavy vehicle adjustment, determined using Highway Capacity Manual methods, and accounting for number of lanes, the work zone capacity model takes the following form:

$$C'' = 1425 * f_{HV} * N$$

where: C'' = adjusted based on the number of lanes open through the work zone (veh/hr)
f_{HV} = heavy vehicle adjustment factor
N = number of lanes open through the work zone.

Data analysis conducted in Phase 2 indicate 1,425 pcphpl is likely too conservative a value if two or more lanes are provided through the work zone and may result in under estimating capacity by as much as 600 pcph for a two lane configuration. To account for this in the model, the 1,425 pcphpl base capacity was replaced with a variable C_B and suggested values, based on the number of discharge lanes through the work zone and are summarized as follows:

- Single lane provided through work zone, C_B = 1,425 passenger car per hour per lane
- Two lanes provided through work zone, C_B = 1,750 passenger car per hour per lane

A general consensus exists among highway engineers and researchers is that work zone intensity does have an effect traffic capacity, however, results from the literature review and data analysis conducted for this project were unsuccessful in quantifying this effect. HCM (10) suggests a base value for capacity can be subjectively adjusted up or down by 10% depending on whether the work zone activity is higher or lower than normal intensity. Another variable (I) has been introduced to the model to account for the intensity of the work zone as well as the number of lane drops. Taking this factor into account, the final form of the work zone capacity equation becomes:

$$C_{WZ} = (C_B + I) * f_{HV} * N$$

where: C_{WZ} = is the estimated capacity of a short-term work zone (veh/hr),
C_B = base capacity
f_{HV} = heavy vehicle adjustment factor
N = number of lanes open through the work zone
I = adjustment factor for type, intensity, length and location of the work activity (As discussed, this value ranges from -146 to +146). If a double lane closure is present, the value for I should be adjusted by -150 in addition to other adjustments.

The work-zone capacity model presented above will likely hold true for long term work zones however, this model is based on data that best fits the definition of short-term work zone lane closures as defined by the MUTCD.

Example Application of the Model

This section illustrates the use of the work zone capacity model developed in the previous section. Given a typical planned three-to-one short-term lane closure with an estimated volume of 1,100 vehicles during its busiest hour, the truck and RV proportions are estimated to be 18% and 2% respectively. Determine whether the closure should be moved to night time hours. The problem solution is provided in a step-by-step fashion as follows:

1. Calculate f_{HV}: Using E_T = 1.90 and E_{RV} = 1.44., f_{HV} = 0.85, from Phase 1 (2) and based on the heavy vehicle equation contained in HCM (10).
2. Calculate C_{WZ}: Based on a double lane closure, an adjustment to I of -150 must included. Assuming average activity, no further adjustment to I is necessary. With N = 1 in this case, using the equation for C_{WZ} = 1,084 veh/hr.

3. Compare volume to capacity: the *V/C* ratio in this example works out to be 1.01 based on V = 1,100 veh/hr and C_{WZ} =1,084 veh/hr.

This *V/C* ratio indicates that the work zone is likely to operate near or at capacity. It is noteworthy that values for base capacities are somewhat conservative thus there is a high probability that speeds through the work zones will be greater than 35 MPH. Regardless, there will be a great deal of congestion even if queues do not form.

CONCLUSIONS AND RECOMMENDATIONS

This research has investigated a variety of factors impacting capacity of short-term lane closures for interstate work zones in South Carolina. Traffic characteristics of freeway work zones were analyzed using classic methods of macroscopic traffic flow modeling. The relationships between speed, density, flow, and time headway were derived using the assumption of a linear relationship between density and speed. When Phase 2 data was combined with Phase 1 data, the statistical goodness of fit of the data to a Greenshields parabola was not very apparent further supporting the more recent literature that suggests the muli-regime format.

A major finding of the Phase 2 research is the performance of three-to-two and three-to-one work zone lane closures. There were too few sites from Phase 1 in this stratification to draw conclusions. Further, even fewer reached capacity during the data collection. In Phase 2 most projects appeared to reach capacity as indicated by the queues.

Proper application of traffic models requires that the effect of trucks and other large vehicles be considered. The normal approach is to convert these vehicles to passenger car equivalents. Evaluation of the average vehicle headways for passenger cars, heavy trucks, and RVs at the various work sites was conducted to determine PCEs for the non-passenger car vehicle classes. There were significant findings that PCEs do increase as speeds reduce. In general, PCEs derived for speed ranges when flows were at or below capacity compared with those outlined for level to rolling terrain in the HCM 2000.

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. A major finding was that double lane closures decrease work zone capacity by nearly 150 pcphpl. No weather related effects could be measured, since short-term work is generally postponed during adverse weather conditions.

The 800 vphpl threshold used by the SCDOT during Phase 1 is considerably lower than values inferred from this project. Further, this value is significantly lower than the values used by all of the states that answered the survey conducted through this study. The value of 1,000 vphpl used for Phase 2 is a considerable increase over the Phase 1 value. Using the average proportion of trucks found on all of the projects, 1,000 vphpl equates to 1,276 pcphpl. On average, the 1,000 vphpl is conservative. However, because of the variability of trucking throughout the state, the researchers recommend that the procedure developed in this study that considers PCEs be used when determining an appropriate threshold value rather than using a single value of 1,000 vphpl. Traffic streams containing large percentages of heavy vehicles will have significantly lower volume thresholds for closure than will streams containing mostly passenger cars. The work zone should be able to pass between 1,200 and 1,400 pcphpl at capacity flow. Upstream volumes are converted to

PCE and compared to the capacity of the work zone. If demand exceeds capacity, queues will develop. Length of these queues will depend upon the duration of the work activity and subsequent demand.

Future Research

Although this research provides solid support for increasing the 800 and 1,000 vphpl standards used by SCDOT, other questions about specific work zone performance remain to be addressed. The 35 work zone sites surveyed did not exhibit sufficient breadth to provide a satisfactory evaluation of the effects of vertical alignment, weather, work zone intensity, and other possible contributing variables. Investigation of these factors would be a fruitful undertaking.

Calibration and validation of the queuing model developed as part of this research requires projects that operate consistently over capacity. It is recommended that a study of oversaturated work zones is conducted. While this would be a controversial endeavor, it is the best way to ensure that the model is accurate. The benefit of such as a study is to be able to accurately predict how long queues will grow and how long they will take to dissipate.

ACKNOWLEDGMENT

The authors gratefully acknowledge the role of the South Carolina Department of Transportation in funding this research effort and providing valuable technical support.

REFERENCES

1. U.S. Department of Transportation, Manual on Uniform Traffic Control Devices, 2003.
2. Sarasua, W. A., D. B. Clarke, and W. J. Davis, *Evaluation of Interstate Highway Capacity in Short-Term Work Zones*, (FHWA-SC-03-02) SC Department of Transportation, May 2003.
3. Sarasua, W., W. Davis, D. Clarke, and J. Kottapally. "*Evaluation of Interstate Highway Capacity for Short-Term Work Zone Lane Closures,"* Transportation Research Record, No. 1877, Maintenance Management and Services 2004, National Academy Press, Washington, DC, pp 85-94.
4. Raymond A. Krammes and Gustavo O. Lopez, "Updated Capacity Values for Short-Term Freeway Work Zone Lane Closures," Transportation Research Record, No. 1442, National Research Council, Washington, DC, 1992.
5. Kim, T., D.J. Lovell, and J. Paracha. "A New Methodology to Estimate Capacity for Freeway Work Zones," presented at the Transportation Research Board Annual Meeting, Washington, D.C., January 2001.
6. Al-Kaisy, A. Hall, F.L. Hall. "Guidelines for Estimating Capacity at Freeway Reconstruction Zone," Journal of Transportation Engineering, 2003, ISSN: 0733947X.
7. Adeli, H. "An Intelligent Decision Support System for Work Zone Traffic Management and Planning," Transportation Research Information Systems, 2004, Report No: FHWA/OH-2004/002
8. Benekohal, RF; Kaja-Mohideen, A-Z; Chitturi, MV, "Methodology for Estimating Operating Speed and Capacity in Work Zone," Transportation Research Record, No. 1833, National Research Council, Washington, D.C., 2004.

9. Chitturi, Madhav, and Rahim Benekohal, "Comparison of Quewz, Fresim and QuickZone with Field Data for Work Zones," Proceedings of the Transportation Research Board 83rd Annual Meeting, Washington, D.C., January 2004.
10. Chitturi, Madhav, and Rahim Benekohal, "Lane Width Effect on Speeds of Cars and Heavy Vehicles in Work Zones," Proceedings of the Transportation Research Board 84th Annual Meeting, Washington, D.C., January 2005.
11. Karen Dixon, J. Hummer and A. Lorscheider, Capacity for North Carolina Freeway Work Zones, Transportation Research Record 1529.
12. Transportation Research Board, Highway Capacity Manual 2000, National Research Council, Washington, D.C., 2000.
13. Greenshields, B.D., "A Study of Traffic Capacity," Highway Research Board Proceedings, Vol. 14, Washington, D.C., 1934, pp.448-477.
14. V.J. Narapesetty, "Passenger Car Equivalents for Short-Term Interstate Work Zone Lane Closures", MS Thesis, Clemson U., December, 2004.