ABSTRACT

FREEWAY SPEED-FLOW RELATIONSHIPS UNDER RAIN AND CONGESTED CONDITIONS

by

Jongho Byun

A procedure to account for the impact of rain and congested conditions on the average speed estimates is provided in this study. Although the Highway Capacity Manual (HCM) provides some discussion on the impact of adverse weather on speed-flow relationships, these impacts are not quantified. Using data collected under rain and congested conditions, a procedure for estimating the average speed under these conditions is provided, which is an improvement over the existing HCM (2000) procedures. Using the speed-flow relationships provided in the HCM (2000) for basic freeway segments as a starting point, new numerical relationships suitable for New Jersey roadways are derived. The new speed-flow relationships can be used to estimate operating speed and level of service (LOS) for New Jersey roadways under rain and congested conditions. The findings are as follows:

- The speed-flow model developed in the research can be used to describe conditions under clear weather, rain, and congested conditions. The model reflects the fact that as flow increases, speed decreases under clear weather and rain conditions. Under congested conditions speed and flow operate on the lower or congested portion of the speed-flow model. In this case, as more vehicles are

added, the discharge flow decreases and the speed also decreases. The speed under rain and congested conditions is higher than the speed under congested conditions.

- Under rain conditions the average speed decreases by about 0.05 mph when the precipitation level is 0.01 inches/hr.
- Both the speed-flow model developed in this research and the HCM (2000) show that the average speed under rain conditions seems to decrease slowly when the flow rate is less than 2000 vphpl. However, the rain adjustment factors, developed using individual roadways reflect the fact that the average speed under rain conditions seems to decrease significantly at low to medium flows and decreases slowly at medium to high flows.

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by
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To my beloved family

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TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

Chapter **Page**

TABLE OF CONTENTS
(Continued)

Chapter **Page**

TABLE OF CONTENTS
(Continued)

LIST OF TABLES

LIST OF TABLES
(Continued)

LIST OF TABLES
(Continued)

LIST OF FIGURES

LIST OF FIGURES
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LIST OF FIGURES
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CHAPTER 1

INTRODUCTION

1.1 Background

Severe weather events can cause millions of dollars of damage to the transportation system and everyday weather events can also negatively impact transportation. Though these effects might not be as easy to see, they include increased delay, number and severity of accidents, fuel consumption, and a decreased efficiency of the transportation system.

1.2 Problem Statement

The impact of adverse weather on freeway traffic operations is a growing concern for roadway management agencies. The Highway Capacity Manual (HCM, 2000) procedure for estimating travel speeds is limited, particularly in the determination of the average speed under adverse weather conditions. Since weather is important factor to consider is the design and operations of freeway facilities, improved procedures are necessary.

In this research, a procedure for estimating the average travel speeds for basic freeway segments during rain and congested conditions is developed. Using data collected under rain and congested conditions, a procedure for estimating the average speed is developed as an improvement over the existing HCM (2000) procedures. The new speed-flow relationships under rain and congested conditions can be used to estimate operating speeds and LOS for freeways in New Jersey.

1.3 Research Objectives

Knowing the impact of rain conditions on the transportation system is necessary to successfully use advisory, control, and treatment strategies in the transportation systems. This research's overall goal is to develop a better understanding of the impacts of rain and congested conditions on traffic flow, speed, and capacity. The specific objectives of the research are as follows:

1. Collect traffic data (e.g., speed, volume, headway, occupancy, etc.) during the peak period and normal/rain conditions from selected New Jersey roadways;
2. Determine the impact of rain and congested conditions on the speed-flow relationship and capacity for freeways in New Jersey; and
3. Develop a speed-flow relationship model for estimating operating speed and LOS for New Jersey roadways

The result of this research will be used to improve the speed-flow relationship provided in the HCM (2000). In addition, the analytical results from this research will be useful to transportation system practitioners in determining operating conditions under rain and congested conditions.

1.4 Organization

This dissertation is structured as follows. Chapter 2 provides a literature review including a review of Greenshields' Model, the speed-flow models in the Highway Capacity Manual, a summary of existing literature on the impact of weather on traffic operations, and speed-flow models which deal with preliminary analysis for comparing congested and uncongested conditions. Chapters 3 and 4 describe the Methodology and Analysis which cover a description of the field data, each study location analysis of, and speed-flow relationships between normal and rain conditions with and without congestion. The chapters then provide an analysis of the data using regression methods. Chapter 5 covers Model Validation. Using a validation data set, the reasonableness of the regression coefficients and ability to generalize influences are drawn from the regression analysis. Chapter 6 describes the developed rain adjustment factors under rain conditions for application of the estimating the average speed under rain conditions. The final chapter contains the conclusions and suggestions for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 History of Speed-Flow Models

2.1.1 Greenshields' Model

It is important to study and to comprehend the history of speed-flow curves to understand the current methodology. Greenshields' paper in 1935 was one of the most influential works on this topic. Greenshields estimated a linear relationship between speed and density. From this relationship, he developed parabolic relationships between flow and density and between flow and speed, as follows:

$$F = S_f\left(D - \frac{D^2}{D_j}\right) \quad OR \quad F = D_j\left(S - \frac{S^2}{S_f}\right) \tag{2.1}$$

where S_f (density = 0) is the free-flow speed, and D_j (speed = 0) is the jam density.

Figure 2.1 shows the speed-flow relationship of Greenshields (1935).

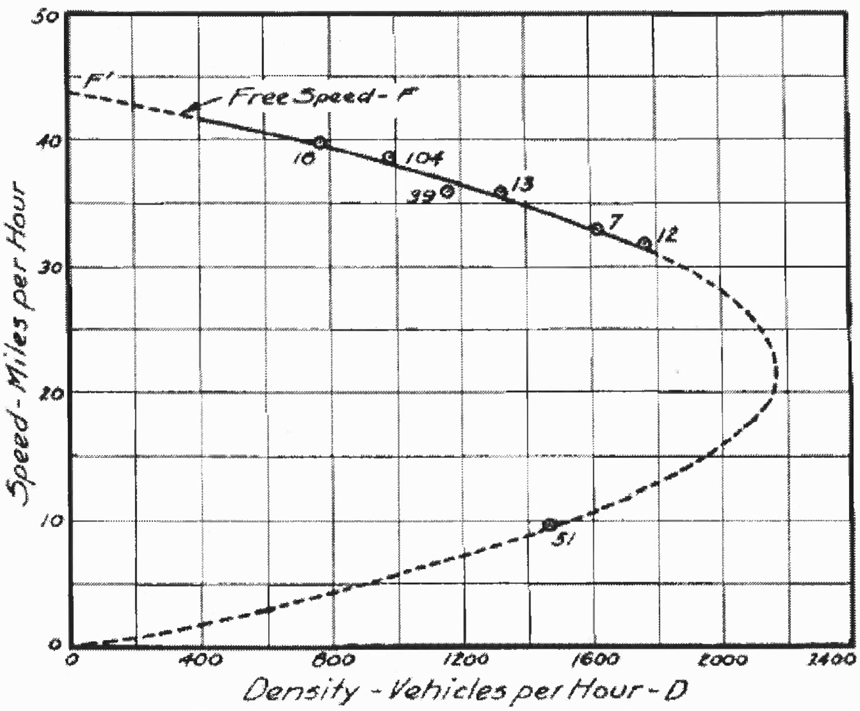


Figure 2.1 Greenshields' Speed-Flow Curve (Greenshields 1935)

The parabolic shape Greenshields (1935) derived was accepted as the proper shape of the curve for decades. In the 1985 High Capacity Manual, the same parabolic shape was retained, although broadened considerably (See Figure 2.6).

Duncan (1976; 1979) concluded that a biased result in relation to the direct estimation of the speed-flow function can be revealed by first calculating the density from the speed and flow relationships, then fitting a line to the speed-density data and converting that line into a speed-flow function that gives a biased result relative to the direct estimation of the speed-flow function.

Greenshields' linear model (1935) of speed and density is expressed as follows:

$$S = S_f\left(1 - \frac{D}{D_j}\right) \tag{2.2}$$

The most interesting aspect of this particular model is that its empirical basis consisted of half a dozen points in one cluster near the free-flow speed, and a single observation under congested conditions. By connecting the cluster of points to the single point, a linear relationship can be drawn as in Figure 2.2.

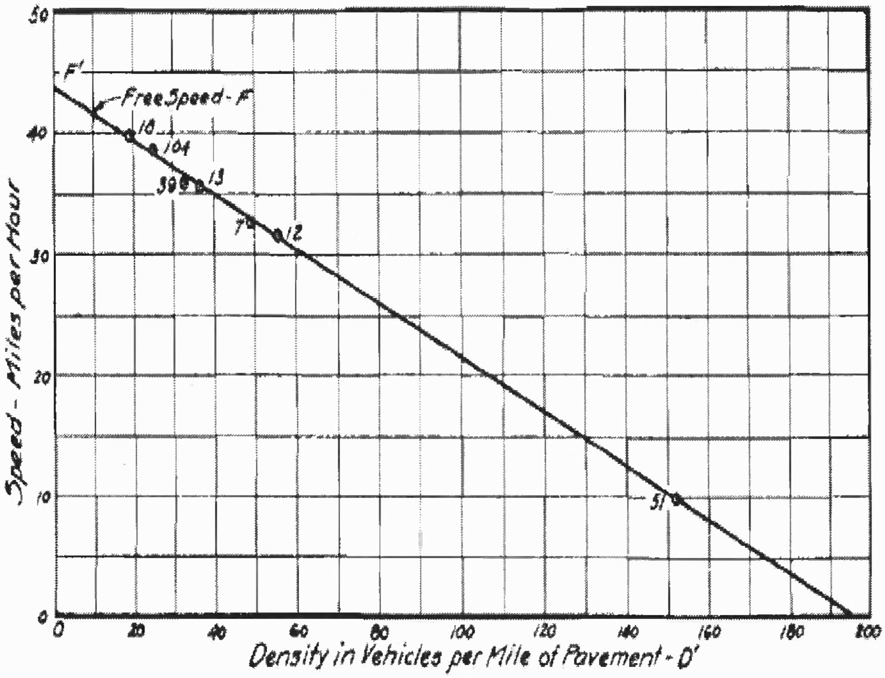
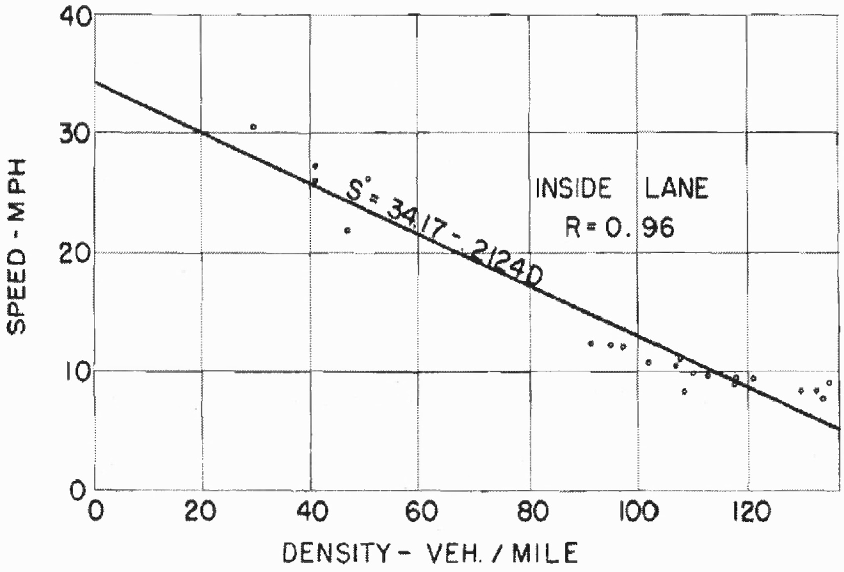
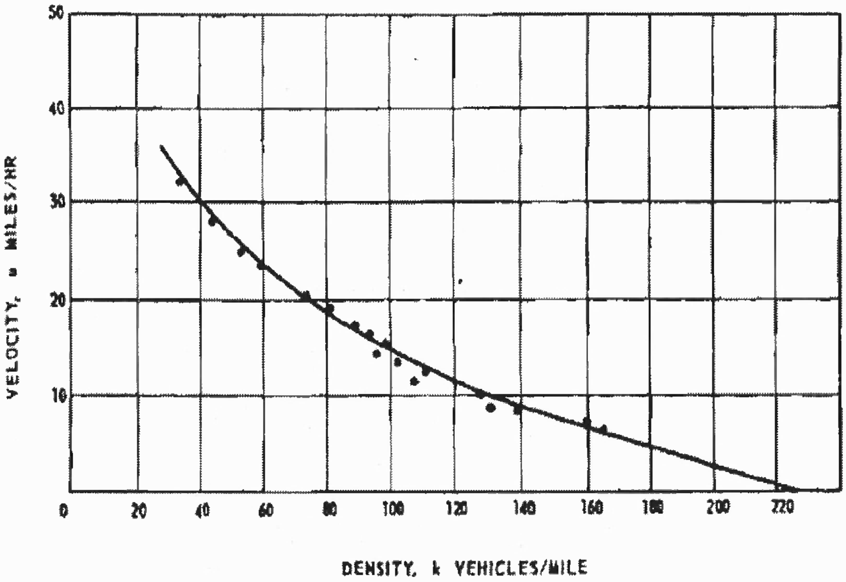


Figure 2.2 Greeenshields' Speed-Density Graph (Greenshields 1935)

There have been many studies which have claimed to confirm Greenshields' model, such as the study that produced Figure 2.3 (Huber 1957). Huber (1957) discussed that speed decreased as volume increased up to a point of critical speed and corresponding critical density. The relationship between speed and volume can be described by a parabolic curve, the apex of which represents the possible capacity at critical speed. The purpose of the study was to determine what factors limited the capacity of two bridges in the west-bound lane and to analyze the characteristics of a rural freeway traffic stream operating under congested conditions caused by continuing speed-reducing roadway conditions.



Linear Form (Huber 1957)



Logarithmic Form (Greenberg 1959)

Figure 2.3 Speed-Density Curves Using a Linear and a Logarithm Forms

2.1.2 Greenberg's Model

A second early model was that put forward by Greenberg (1959), showing a logarithmic relationship:

$$S = c \ln\left(\frac{D}{D_j}\right) \tag{2.3}$$

where c is the optimum speed.

Greenberg's paper showed the fit of a model that had two data sets. The first data set was derived from speed and headway data of individual vehicles. The data was separated into speed classes and the average headway was calculated for each speed class (Greenberg, 1959). In other words, the vehicles that appear in one data set (speed class) may not even have been traveling together. The density can always be calculated as the reciprocal of the average headway, but the meaning of density becomes perplexing when that average is taken over vehicles that may not have been traveling together. Another important factor is that lane changing was not permitted in the Lincoln Tunnel where the data was obtained in 1955; consequently, the data represent single-lane rather than freeway operations. In the second data set shown in Figure 2.3 (Huber 1957), Huber's information was used by Greenberg; Greenberg's graph is shown in Figure 2.3 (Greenberg 1959). The curve does not improve much, even though the curve fits nicely because Huber reported an R^2 of 0.96.

2.1.3 Comparison of Models

An important empirical test by Drake et al. in 1967 investigated Greenshields' and Greenberg's speed-density curve, plus five other speed-density curves. The five curves investigated included: (1) a two-part, (2) a three-part piecewise linear model, (3) Underwood's transposed exponential curve, (4) Edie's discontinuous speed exponential form (which combines the Greenberg and Underwood curves), and (5) a bell-shaped curve. Table 2.1 shows the five speed-flow equations and Greenshields' equation. The model functions used were quadratic and logarithmic forms for uncongested conditions and quadratic and exponential forms for congested conditions. Flow rate is a dependent and speed is an independent varibale in the equations.

Table 2.1 Previous Speed-Flow Equations

Speed-Flow	Form	Uncongested Conditions	Congested Conditions
Greenshields	**Quadratic**	$F = 126.02S - 2.15S^2$	
Two-Regime	**Quadratic**	$F = 118.2S - 1.94S^2$	$F = 150.9S - 3.7S^2$
Greenberg	**Exponential**	$S = 48$	$F = 145.5Se^{-\frac{S}{32.8}}$
Underwood	**Logarithm**	$F = 56.9S\ln\left(\frac{76.8}{S}\right)$	
Edie	**Logarithm** **+Exponential**	$F = 163.9S\ln\left(\frac{54.9}{S}\right)$	$F = 162.5Se^{-\frac{S}{26.8}}$
Bell-shaped	**Logarithm**	$F = \frac{S^2}{0.00013}\ln\left(\frac{48.6}{S}\right)$	

Data from the middle lane of the Eisenhower Expressway in Chicago was used in the test to obtain information over as much of the range of operations as possible. One-minute observations were initially collected and the measured data consisted of volume, time mean speed, occupancy and density. Density was calculated from volume and time mean speed. A sample was then taken from among the 1224 data points to create a data set that was uniformly distributed along the density axis in accordance with regression analysis of speed on density. The observations were recorded with the pilot detection system of the Chicago Area Expressway Surveillance Project. The observations were made between 1:00 am and 6:00 pm on four weekday afternoons under dry and normal traffic conditions. Thus, many of the data represented peak hour characteristics, while few were associated with the very lowest density range. The study used a variety of statistics to compare the seven speed-density speed hypotheses and thereby to select the best one. In this test, the statistical analyses proved inconclusive.

Almost all conclusions were based on intuition alone since the statistical tests provided little decision power after all. Despite the statement above, twenty-one graphs assisted considerably in differentiating among the seven hypotheses and the results of both speed-volume and volume-density graphs. Therefore, the assertion that intuition was the only basis in the research seemed over-exaggerated. Figure 2.4 provides an example of one of the three types of graphs used in the test based on Edie's model (Drake et al., 1967).

Drake (1967) commented that the Edie formulation gave the best estimates of the fundamental parameters. The standard error was the lowest of all hypotheses. With respect to Figure 2.4, Edie's model was the only one of the seven to replicate capacity operations closely on the volume-density and speed-volume curves.

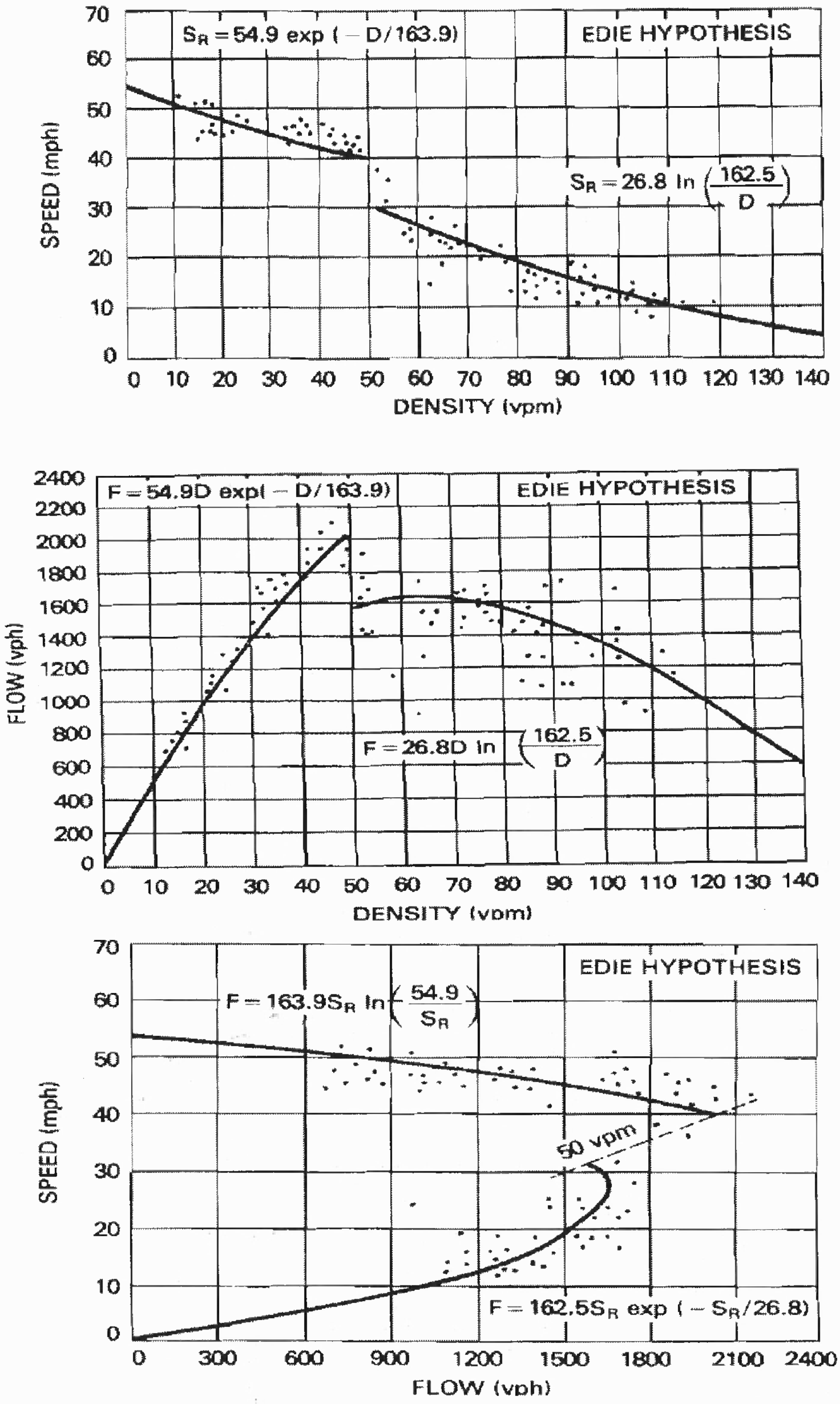


Figure 2.4 Edie's Hypothesis for the Speed-Density Function, Fitted to Chicago Data (Drake et al. 1967)

In comparison to the Edie model, the other models underestimated the maximum flows, often by a considerable margin, as illustrated in Figure 2.5. Figure 2.5 shows the speed-volume curve resulting from Greenshields' hypothesis of a linear speed-density relationship. Overall, the study executed by Drake et al. showed that none of the seven models provided a particularly good fit or an explanation of the data and they dealt with each model separately.

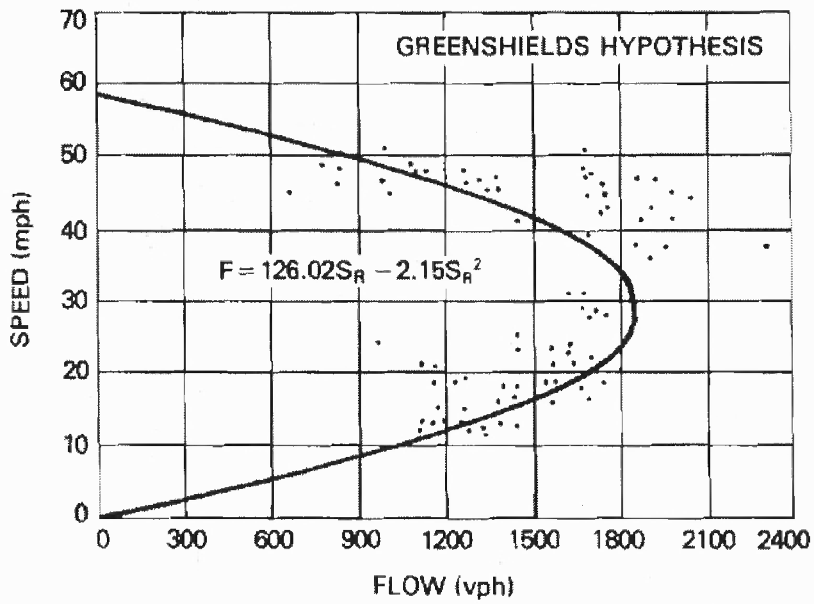


Figure 2.5 Greenshields' Speed-Flow Function Fitted to Chicago Data (Drake et al. 1967)

Two additional issues of significance arose from the Drake et al. study (1967). The first issue was methodologically identified by Duncan (1976; 1979) which was discussed earlier with regards to Greenshields' work. Duncan explained the three steps of the procedure: (1) calculating density from speed and flow data, (2) fitting a speed-density function to that data, and then (3) transforming the speed-density function into a speed-flow function. This procedure resulted in a method that did not fit the original speed-flow data particularly well. This three step procedure method was used by Drake et al. in turn. Most of their resulting speed-flow functions did not fit the original speed-flow data. Duncan's 1979 paper expanded on the difficulties to show that minor changes in the speed-density function led to major changes in the speed-flow function. This result suggests the need for future caution in using this method (the slopes of the speed/flow line in terms of traffic composition and road layout) to calibrate a speed-flow curve.

The second issue is the relationship between car-following models and the models tested by Drake et al. Four of the models they tested have been shown to be directly related to specific car-following rules according to the cited articles by Gazis, Herman, and Rothery (1959; 1961). An interesting question to ask in regards to the overall work of Drake et al. is whether the results raise questions about the validity of car-following models for freeways. Four of the speed-density models tested by Drake et al. originate from the car-following models. The results of their testing suggest that the speed-density models are not particularly good, and this suggest the possibility that the car-following models are not valid for freeways.

2.1.4 Car Following Model

Rakha and Crowther (2002) compare three car-following models. These models include Greenshields' single-regime model, Pipes' two-regime model, and a four-parameter single-regime model that combines both Greenshields' and Pipes' models. The four-parameter model that was proposed by Van Aerde (1995) and Van Aerde and Rakha (1995) are less known. It was found that Greenshields' single-regime model requires two calibrated parameters: free-flow speed and either capacity or jam density. Alternatively, Pipes' two-regime car-following model requires three calibrated parameters: free-flow speed, jam density, and a driver sensitivity factor. Finally, the four parameter single-regime model that was proposed by Van Aerde (1995) and Van Aerde and Rakha (1995), while requiring four parameters for calibration, provide more degrees of freedom to reflect different traffic behavior across different roadway facilities. The proposed modification, to the calibration procedures of the Pipes model offers an avenue to calibrate microscopic car-following behavior using macroscopic field measurements that are readily available from loop detectors. The parameters of modification include road capacity, spacing of vehicles at jam density and roadway free speed.

2.2 Speed-Flow Models in Highway Capacity Manual

2.2.1 HCM 1985

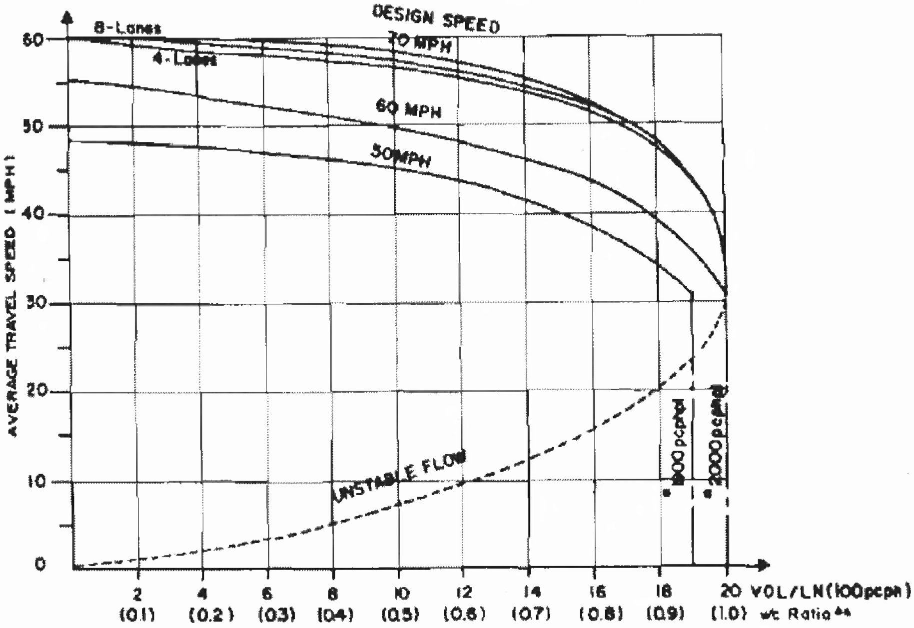
Highway capacity estimation is fundamental to the study of traffic. In the Highway Capacity Manual (HCM 1985), highway capacity is defined as "the maximum sustained 15 minute flow rate, expressed in passenger cars per hour per lane, that can be accommodated by a uniform freeway segment under prevailing traffic and roadway conditions in one direction of flow." The observed 15-min flow rate, which is used to estimate highway capacity, can vary depending on the traffic conditions and roadway conditions. Because of this reason, highway capacity as defined by HCM 1985 is not generally an acceptable definition.

The HCM 1985 method proceeds as the following: (1) detects 15 minute-base traffic data (speed, volume, and density), (2) searches for a speed-volume-density relationship using data from step (1), and (3) determines highway capacity.

The most important conceptual change of HCM 1985 is the reference to “hourly rate.” The methodologies of the 1985 HCM do not generally deal with full rates of flow during a peak 15 minute interval within the analysis hour. One or 15-minute rates of flow are statistically unstable. This means that, in most cases, no statistically acceptable relationships can be established between flows and other traffic parameters for such short periods. When 15-minute flows are considered, statistically stable relationships can be and have been established. Thus, 15 minutes was selected as the minimum time period to be considered in capacity analysis.

In general, the 1985 HCM (Figure 2.6) suggests for lower speeds and a lower capacity in comparon with the HCM 1994.

Additional empirical work dealing with the speed-flow relationship was conducted by Banks (1990), Hall and Hall (1990), Agyemang-Duah and Hall (1991) and Ringert and Urbanik (1993). All of these studies supported the idea that speeds remain nearly constant even at quite high flow rates.



* capacity
** v/c ratio based on 2000 pcphpl valid only for-60 and 70-MPH design speeds

Figure 2.6 Speed-Flow Curves (HCM 1985)

Figure 2.7 shows such a drop in average speed on the basis of two studies. There was roughly a three percent drop in average speed from pre-queue flows by Banks (1990), on the basis of nine days of data at one site in California. Also, Agyemang-Duah and Hall (1991) found about a 5 percent decrease in average speed, with 52 days of data at one site in Ontario. In many locations, high flow rates do not last long enough prior to the onset of congestion to yield the stable flow values that would show the drop; consequently, the decrease in flow is not easily noticeable.

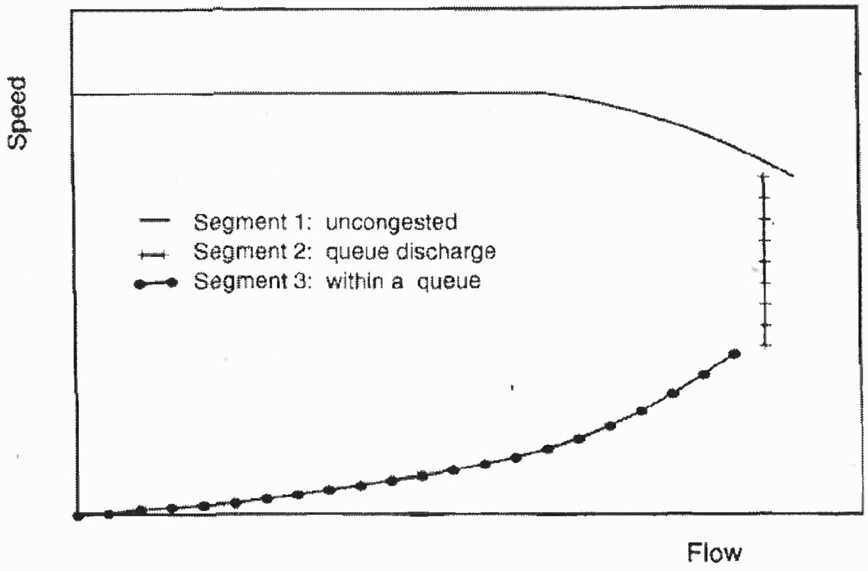
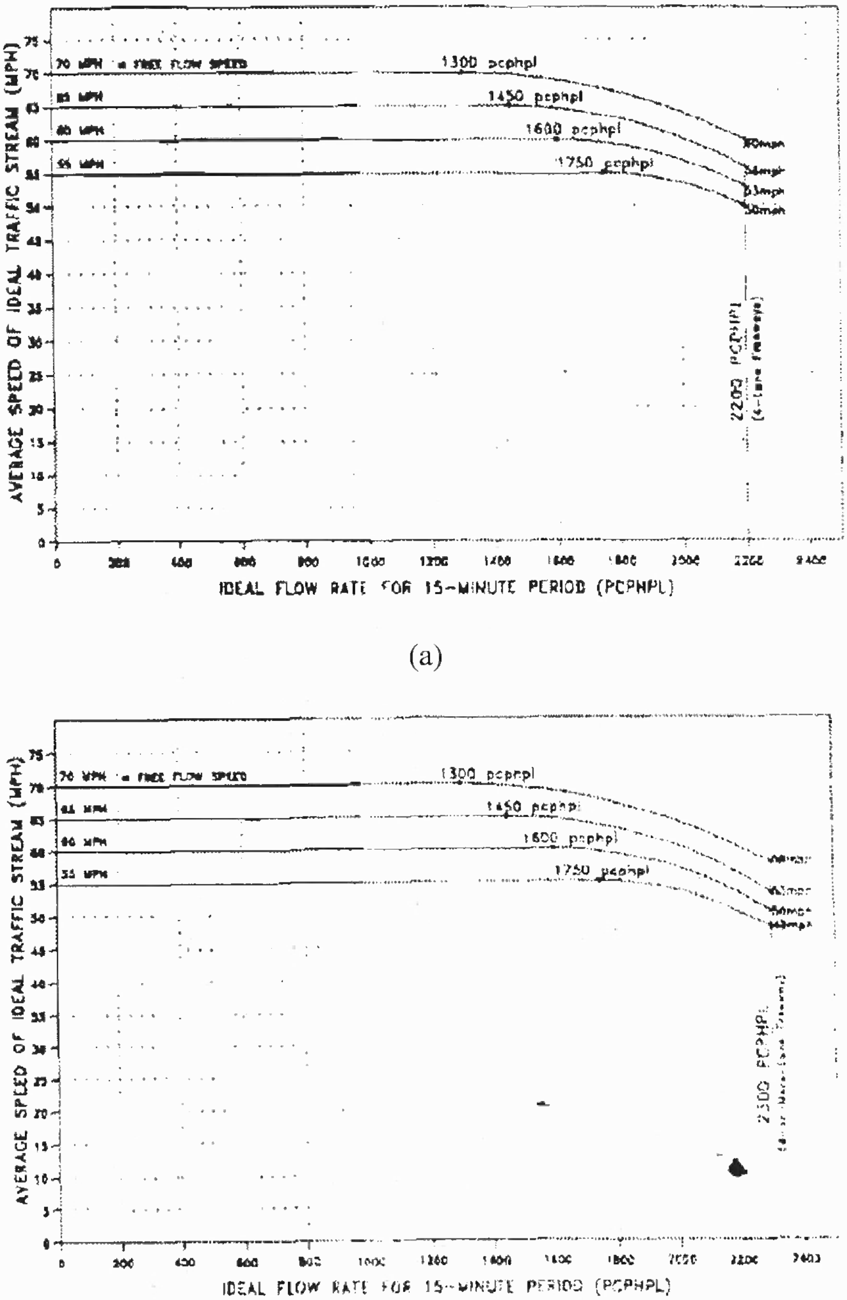


Figure 2.7 Speed-Flow Curves: Proposed by Hall, Hurdle, & Banks (Hall et al. 1992)

2.2.2 HCM 1994

The 1994 Highway Capacity Manual contains the speed-flow curve shown in Figure 2.8. In Figure 2.8, the average speed remains flat as flows increase to an area between a half and two-thirds of capacity values, and decreases in speeds slightly at capacity from those values. The curves in Figure 2.8 identify generalized empirical results, but they do not represent any theoretical equation (Hall, Hurdle, and Banks, 1992). There is not really any theory that would explain these particular shapes except perhaps for Edie et al. (1980), who propose qualitative flow regimes that relate well to these curves.



(a)

(b)

Figure 2.8 Speed-Flow Curves (HCM 1994)

The speed-flow theorists' task is to develop a consistent set of equations. Fundamentally, the research differs considerably from the earlier work, which tended to start from hypotheses about first principles and to include data only late in the process (Hall, Hurdle, and Banks, 1992). In a paper by Hall, Hurdle, and Banks (1992), the bulk of the empirical work on the relationship between speed and flow was summarized. In it, they proposed the model for speed-flow shown in Figure 2.7.

In Figure 2.8, the revision of the HCM in 1994 improves on the curve of Figure 2.7 by specifying the curve to reconsider the situation of the freeway. The curves in the previous figures depended on the free-flow speed: the breakpoints at which speeds started to decrease from free-flow, and the speeds at capacity. Although these aspects of the curve were only assumed at the time that the curves were proposed and adopted, they have since received some confirmation in a paper by Hall and Brilon (1994). Hall and Brilon looked at German Autobahn information and a paper by Hall and Montgomery (1993) drew on British experience.

The speed-flow curve in the manual for cost-benefit analyses is shown in Figure 2.9. The figure shows a decline in speed (of 6 km/hr) per each additional 1000 vehicles per hour per lane from the first vehicle on the road. But a detailed inspection of the data in the conclusion (Duncan 1974) shows that the data are ambiguous, and it could easily support a slope of zero out to about the breakpoint of 1200 vphpl (Hall and Montgomery 1993).

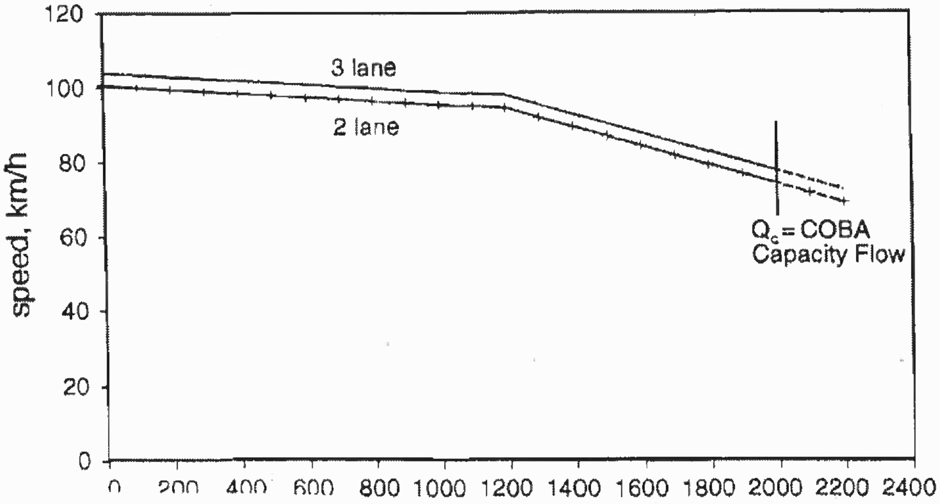
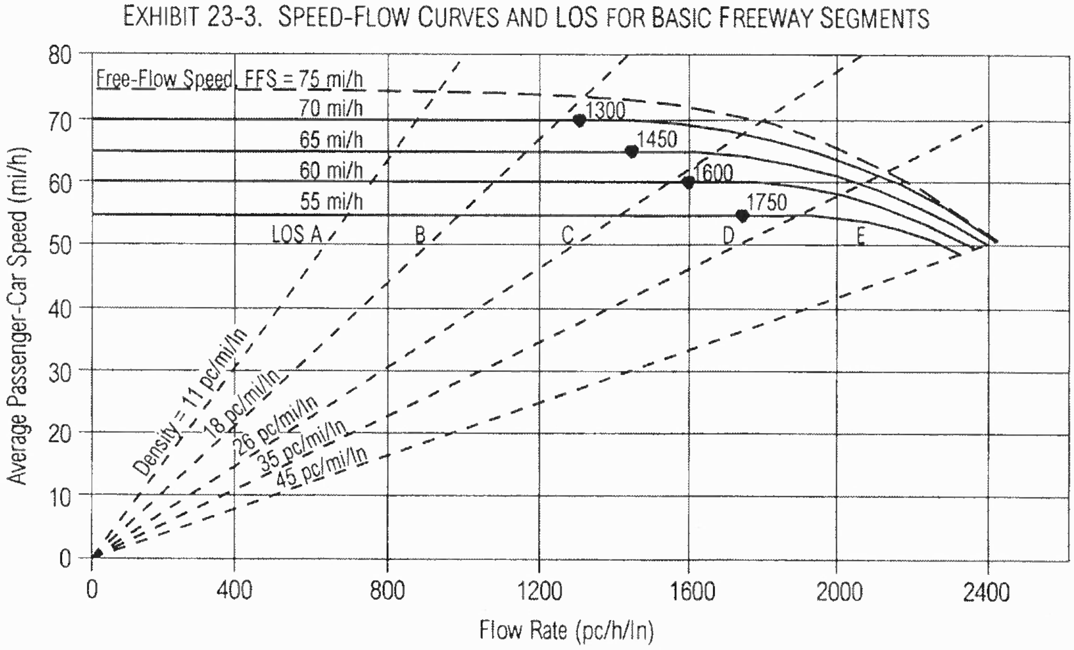


Figure 2.9 UK Speed-Flow Curves (Source: Ducan 1974)

2.2.3 HCM 2000

In Figure 2.10, free-flow speed is estimated through an improved algorithm which accounts for the effects of various freeway design characteristics, including lane width, shoulder width, number of freeway lanes and interchange density (HCM 2000). The ideal capacity of a basic freeway segment is found to be a function of free-flow speed. It is estimated to range between 2,250 passenger cars per hour per lane (pcphpl) and 2,400 pcphpl, and to occur at densities ranging from 43.6 to 46.0 pcpmpl. A speed-flow curve has been included for free-flow speeds of 75 mph. The need for this curve became apparent when the federally mandated speed limits were removed, but unfortunately these mandates were not eliminated until after data were collected. Therefore, this curve was developed through extrapolation.



For 70<FFS<75 mph, (3400-30FFS)<v_p<2400, $S = FFS - \left[\left(FFS - \frac{160}{3}\right)\left(\frac{v_p + 30FFS - 3400}{30FFS - 1000}\right)^{2.6}\right]$

For 55<FFS<70 mph, (3400-30FFS)<v_p<(1700+10FFS), $S = FFS - \left[\frac{1}{9}(7FFS - 340)\left(\frac{v_p + 30FFS - 3400}{40FFS - 1700}\right)^{2.6}\right]$

For 55<FFS<75 mph, v_p<(3400-30FFS), $S = FFS$

Figure 2.10 Speed-Flow Curves (HCM 2000)

2.3 Summary of Existing Literature on Weather Impacts

2.3.1 Impact of Capacity

Limited studies have been conducted to directly address how adverse weather affects various speed-flow variables such as capacity and other traffic parameters. Jones et al. (1970) found that in the event of rain, the capacity of a segment of Interstate 45 in Houston, Texas was reduced by 14 to 19 percent. A similar study of Interstate 35W in Minneapolis, conducted by Ries (1981), estimated and compared capacities for the roadway under rain and snow. The study concluded that the slightest amount of precipitation reduced the capacity by 8 percent. The study found that each additional 0.01 inches/hr of rain decreased capacity by 0.6 percent, and the impact of snow was more severe than that of rain. Every 0.01 inches/hr of snow decreased capacity by 2.8 percent.

Hall and Barrow (1988) investigated the impacts of adverse weather on the flow-occupancy relationship for Queen Elizabeth Way near Hamilton, Ontario. During rainstorms, traffic flow changed from uncongested to congested at lower occupancy rates, thus implying that capacity is reduced. They also found that the traffic volume was also a factor in determining weather congested conditions when it was raining or snowing.

Brilon and Ponzlet (1996) observed a reduction of freeway capacity on the Autobahn by 350 vph when there were two lanes in each direction and more than 500 vph when there were three lanes in each direction.

When addressing freeway capacity reduction due to weather in Chapter 22 of the Highway Capacity Manual 2000, the following is stated and Table 2.2 shows the summary of capacity reductions.

- No significant reductions in capacities due to light rains until visibility is affected
- Light snow causes 5% to 10% reductions in capacities
- Heavy rain causes 14% to 15% reductions in capacities
- Heavy snow causes 25% to 30% reductions in capacities

Table 2.2 Summary of Capacity Reductions

	Light rain	Heavy rain	Light snow	Heavy snow
Jones et al. (1970)	14 - 19%		-	-
Ries (1981)	0.6%	-	2.8%	-
HCM 2000	-	14-15%	5-10%	25-30%
Brilon and Ponzlet(1996)	350vph for 2 lane		500vph for 3 lanes	

2.3.2 Impact of Speed

Liang et al. (1998) studied the impact of visibility on a 25-km segment of Interstate 84 in Idaho. Automatic traffic counters, point detection systems with a forward scatter detection technology, and one laser ranging device were utilized to collect traffic volume and visibility. Speed data from foggy days revealed an average speed reduction of 5 mph when compared to average clear day speeds. On snowy days, the speed of cars was affected by visibility and other variables. A generalized linear model was developed that described speed as a function of visibility, snow cover, light, temperature, and wind. Overall, an average speed reduction of 19.2 km/hr was observed during snow events, and the speed reduction was highly variable.

Lamm et al. (1990) categorized weather events and evaluated their impact on operating free-flow speeds. Twenty-four rural two-lane highways during dry and wet conditions were studied but there was no statistical difference in operating speed because visibility was not limited during any of the rain events considered.

Although the works by Brilon and Poszlet (1996) and by Ibrahaim and Hall (1994) are very insightful, neither study was conducted on U.S. roadways. Particularly, the Ibrahaim and Hall study used an extremely small data set (they used only six clear, two rainy, and two snowy days). Data analyzed were restricted to data obtained during free-flow conditions (uncongested flow). Dummy variables for different weather conditions (light and heavy rain and light and heavy snowfall) were used. A dummy variable can take the value at 0, 1 and 2 for different weather conditions (e.g., 0 = clear, 1 = light rain and snow, and 2 = heavy rain and snow). They found that traffic operations were statistically different for each type of weather. Brilon and Poszlet (1996) found vehicle speeds in Germany were reduced by 3.1 mph (5 km/hr) at night and 5.9 (4 lane) to 7.4 mph (12 lane) (9.5 to 12 km/hr) when roadways were wet. Ibrahim and Hall (1994) found site-specific reductions in free-flow speed of 1.2 mph (2 km/hr) for light rain, 1.9 mph (3 km/hr) for light snow, 3.1 to 6.2 mph (5 to 10 km/hr) for heavy rain, and 23.6 to 31.0 mph (38 to 50 km/hr) for heavy snow.

In a rural section of I-84 in the U. S., Kyte et al. (2000) gathered data in treacherous weather conditions: fog, blowing snow, high winds and other weather conditions by using already installed traffic and environmental sensors. The impact of traffic operations by four environmental variables - precipitation intensity, wind speed, visibility, and road surface condition (dry, wet, or icy/snowy) - were compared to normal conditions. The impacts of different weather conditions were as follows: wet roadway conditions reduce speeds by 4.5 km/hr, snow and ice reduce speeds by 9.1 km/hr, and wind speeds from 16 to 32 km/hr reduce speeds by an average of 5 km/hr. Therefore, if there are wet pavements and wind speeds from 16 to 32 km/hr, the reduction in speed is expected to be 9.5 km/hr.

Bernardin et al. (1995) assessed several traffic parameters: saturation flow, vehicle speeds, lost time, and capacity during extreme winter weather on a roadway network in Anchorage, Alaska. The researchers found that the traffic parameters are severely affected by winter and extreme conditions because of slower vehicle speeds. They also found that adverse weather tends to decrease travel speed by 13 percent and increase average delay by 23 percent.

The economic impacts of adverse weather on all types of highways were assessed by FHWA (1977). The severe weather impacted fuel consumption and work delay. For these studies, interstate speeds were measured in varying degrees of inclement weather. The seven conditions are defined in below Table 2.3 and Table 2.4 shows the summary of adverse weather speed reductions.

Table 2.3 Adverse Weather Speed Reductions

Condition	Percent Reduction
Dry or Wet	0%
Wet and Snowing	13%
Wet and Slushy	22%
Slushy in Wheel Paths	30%
Snowy and Sticking	35%
Snowing and Packed	42%

Source: FHWA (1977)

Table 2.4 Summary of Speed Reductions

	Light rain	Heavy rain	Light snow	Heavy snow	Night	Wet
Liang et al. (1998)	-	-	-	19.2	-	-
Kyte et al. (2000)	-	-	-	-	4.5	9.1
Bernardin et al. (1995)		Average	13%			
FHWA (1977)			See the	Table 2		
Ihrahim and Hall (1994)	2	5-10	3	38-50	-	-
Brilon and Ponzlet (1996)	-	-	-	-	5	9.5*-12**

Unit: km/h
* 4 lane
**12 lane

2.3.3 Impact of Between Capacity and Speed

Agarwal, Maze, and Souleyrette (2005) examined speed-flow on metro freeways in the vicinity of the Twin Cities and evaluated the impact of rain, snow, and various pavement surface conditions. The research used four years of detector occupancy information from roughly 4,000 detectors, information accumulated over the same period from three Automated Surface Observing Systems (ASOS) at nearby airports, and from data of pavement surface conditions in a two-year period from five road weather information system (RWIS) sensors in a nearby freeway system. The rain and snow events were separated according to intensity levels and their impact on the speed, and the headway and the capacity of roadways was noted.

In the study, severe rain and snow caused the most significant reductions in capacities and operating speeds. Heavy rains of more than 0.25 inches/hr and heavy snow of more than 0.5 inches/hr showed capacity reductions of 10 – 17 percent and 19 – 27 percent and speed reductions of 4 – 7 percent and 11 – 15 percent, respectively. Compared to the Highway Capacity Manual (2000), the results showed significant speed reductions due to heavy rain and snow, because the Highway Capacity Manual (2000) may underestimate or overestimate the impacts.

2.3.4 Impact of Delay

Botha and Kruse (1992) conducted a study to show how adverse weather reduces saturation flow rates. The study investigated the adverse effects of residual ice and snow on saturation flow rates and delay times at signalized intersections in Fairbanks, Alaska. In comparison to the HCM, the winter data collection and subsequent analysis showed that winter saturation flow measurements were much less than those suggested in the HCM. It was found that when snow and ice were prevalent, saturation flow rates were 19 percent lower than the recommended HCM rates.

In a study by Kwon, Mauch, and Varaiya (2006), it was found that incidents and special events together account for 17.8 percent of total delays. A large 33 percent of all delays could be eliminated by ideal ramp metering. Excess demand causes 47 percent of total delay and lastly, rain caused 1.6 percent of delays.

Han, Chin, and Hwang (2003) laid a framework for determining the impact of adverse weather conditions in terms of delay in the United States. It was found that adverse weather conditions cause approximately a 1 to 6 minute delay, which is an increase of 7 to

36 percent of the normal travel time. American drivers have a very low probability (0.6%) of experiencing a moderate travel delay due to adverse weather conditions on their typical trips during any day in 1999. The majority of delays occurred during winter and early spring. Table 2.5 shows the summary of delay reductions.

Table 2.5 Summary of Delay Reductions

	Light rain	Heavy rain	Light snow	Heavy snow	Night	Wet
Botha and Kruse (1992)	-	19% for	Saturated	flow rate	for snow	-
Kwon et al.(2006)	1.6% for	rain	-	-	-	-
Han et al. (2003)		Average	0.6%			

2.3.5 Impact of Volume

An approximately 29 percent decrease in vehicle volume was reported by Knapp (2001) during an average winter storm condition. The reductions varied by location from approximately 16 to 47 percent and three events even showed an increase in traffic volume. The percent volume reduction correlated with total snowfall plus the square of maximum gust wind speed.

Knapp, Smithson, and Khattak (2000) analyzed the mobility impacts of winter storm events. In the study, roadway and weather data and hourly traffic volumes were acquired from the Roadway Weather Information System (RWIS), from Automatic Traffic Recorders (ATRs), and Analysis System (ALAS) respectively. Daily snowfalls were acquired from state and national agencies. Data from seven interstate roadway segments were considered under both severe and fair weather conditions. Specifically, winter storm events with single duration of four or more hours and a snowfall of 0.51 cm/hr (0.20 inches/hr) or more were evaluated. The impacts of winter weather on freeway traffic were evaluated.

The winter storm events decreased traffic volumes but with multiple variables (e.g., wind plus snow etc). The average winter storm volume reduction was approximately 29 percent with a range from approximately 16 to 47 percent. The total snowfall and the square of maximum gust wind speed correlated positively with the percent volume reduction. Table 2.6 shows the summary of volume reductions.

Table 2.6 Summary of Volume Reductions

	Light rain	Heavy rain	Light snow	Heavy snow	Night	Wet
Knapp (2001)	-	-	-	29%	-	-
Knapp et al. (2000)	-	-	-	0.51cm/h (0.2inch/h)	-	-

2.3.6 Impact on Crashes

Knapp, Smithson, and Khattak (2000) found that there was a significant increase in crash rates during winter storm events; this may be due to a large decrease in traffic volumes and higher crash reporting rates during winter weather. When traffic volume decreases, the crash rate can be higher due to the traffic speed. When the increase in snowfall intensity and the duration of the snowstorm was controlled for in the data, the frequency of winter storm crashes increased. The results of this research can assist in determining the potential impact of winter weather. Also, the results can be utilized to further support the eventual development of a level of service system under winter weather and to assist in planning preventive and emergency operations.

Knapp (2001) mentioned that when comparing an analysis of winter storm events with fair weather conditions, the crash rate significantly increased during storm events; detailed statistical analysis showed that the winter storm crash frequency was positively related to exposure, to event duration, and to intensity of snowfall.

2.3.7 Impact on Travel Time

Stern, Shah, and Goodwin (2003) showed that there was at least an 11 percent increase in peak period travel time with any type of precipitation. Regression analyses used to show that different weather variables such as visibility, wind, and precipitation increase travel time by approximately 13 percent. When the impact of precipitation was measured separately during the off-peak timeframe, the precipitation caused a 3.5 percent increase in travel time. However, due to the limitations of data, the estimates are likely to be lowered.

2.3.8 Speed-Flow Studies

Uncongested Condition

Ibrahim and Hall (1994) discussed the effects of adverse weather conditions by using flow-occupancy and speed-flow relationship studies. The data used in the analysis were obtained from the Queen Elizabeth Way Mississauga freeway traffic management system.

Regression analyses were performed to select proper models representing the flow-occupancy and speed-flow relationship for free-flowing traffic operation. Then dummy variable multiple regression analysis techniques were used to test for significant differences in traffic operations between the different weather conditions. The technique used a dummy variable with the value of 1 and 0 to distinguish between two data sets. For speed-flow data, the 30 second observations of the data showed high scatter, which made it difficult to predict a good model for this relationship. The analysis was conducted to test the goodness of the fit of a piecewise linear model. The comparison analysis used two dummy variables. The first tested the difference between normal and light rain (dummy1=0 for normal, 1 otherwise), and the second tested the difference between light and heavy rain (dummy2=1 for heavy rain, 0 otherwise).

The study by Ibrahim and Hall concluded that the adverse weather conditions reduced the slope of the flow-occupancy function and maximum observed flow rates while causing a downward shift in the speed-flow function.

Congested Condition

Zhou and Hall (1999) investigated the relationship between speed and flow within traffic congestion representing the lower portion of the standard curve. It also identified an equation to describe this portion of the relationship. Data were obtained from the Gardiner Expressway RESU System and Highway 401 COMPASS System in Toronto, Ontario.

Dummy variable regression was used and each day was considered as potentially a separate class, and differential effect for each was compared against a default day through the coefficients of a dummy (0, 1) variable. If the coefficients are statistically significant for any day, it would indicate that different coefficients were needed for the day in question. If the coefficients are not significant, the data for that day can be grouped together with the data for the default day to provide the best estimate of the regression parameters.

In relation to the shape of the speed-flow curve during traffic congestion, there are a number of key principle findings. First, it is important to incorporate the full range of data to fit a curve to represent the congestion part of the speed-flow curve; therefore, data from several sites may be needed. Despite the combination of sites, there is often what might be termed a "data gap" between easily available congestion data (up to perhaps 1,800 vphpl) and flow rates for queue discharge flow.

The data gap information shows that speed increases significantly under congested conditions at rapidly high congestion flows; it also appears to be a difference in the speed-flow relationship when the construction is underway. If distinct curves for different freeway (or free-flow) speeds for the top half of the speed-flow relationship is apparent, it seems reasonable to assume that there will be differences for the bottom half. Since operations within the queue are governed by the downstream queue discharge, downstream conditions such as construction can affect the speed-flow curve itself at an upstream location. But this differs from what one expects for the other two segments of the speed-flow curve.

In a study designed by Ringert and Urbanik II (1993), different results were discovered. First, variance in flow rate decreases after the speed drop under queue discharge. Second, peak flows for individual lanes occur in free-flow conditions before breakdown. Third, with an imbalance of flow rates between individual lanes, not all lanes had peak flows during free-flow conditions. A premature transition of flow from free-flow into queue discharge conditions occurs. Fourth, a bottleneck configuration may influence the maximum possible flow obtainable during free-flow and possible queue discharge conditions. Lastly, queue discharge appears to be the best estimate for maximum sustainable flow and capacity.

Hall and Hall (1990) stated in the study that speed-flow relationships are investigated downstream of a queue to identify capacity flows and the effects of formation of upstream queue on speed and flow. Results show markedly different shapes for the speed-flow curves in the queue and the downstream; thus, it creates uncertainty to the efforts in developing general speed-flow curves for specific facility types. In a bottleneck downstream of the queue, capacity was found to be approximately 2,300 passenger-car units per hour per lane but queue formation did not have any effect on the flow rates and observed speeds. The net rate of flow at the downstream bottleneck influenced the maximum observed flow in the queue. Downstream of a queue maintained constant speeds until the queue formed upstream and there was a vertical drop to lower speeds at roughly the same flow rates.

Speed-flow curves in the bottleneck and in the queue were identified in the study. In locations downstream of the head of the queue and in the bottleneck were shown by one curve serving to identify both operations expected before upstream breakdown (horizontal line), and the speeds expected (at the maximum flow) at different distances downstream of the head of the queue.

CHAPTER 3

METHODOLOGY

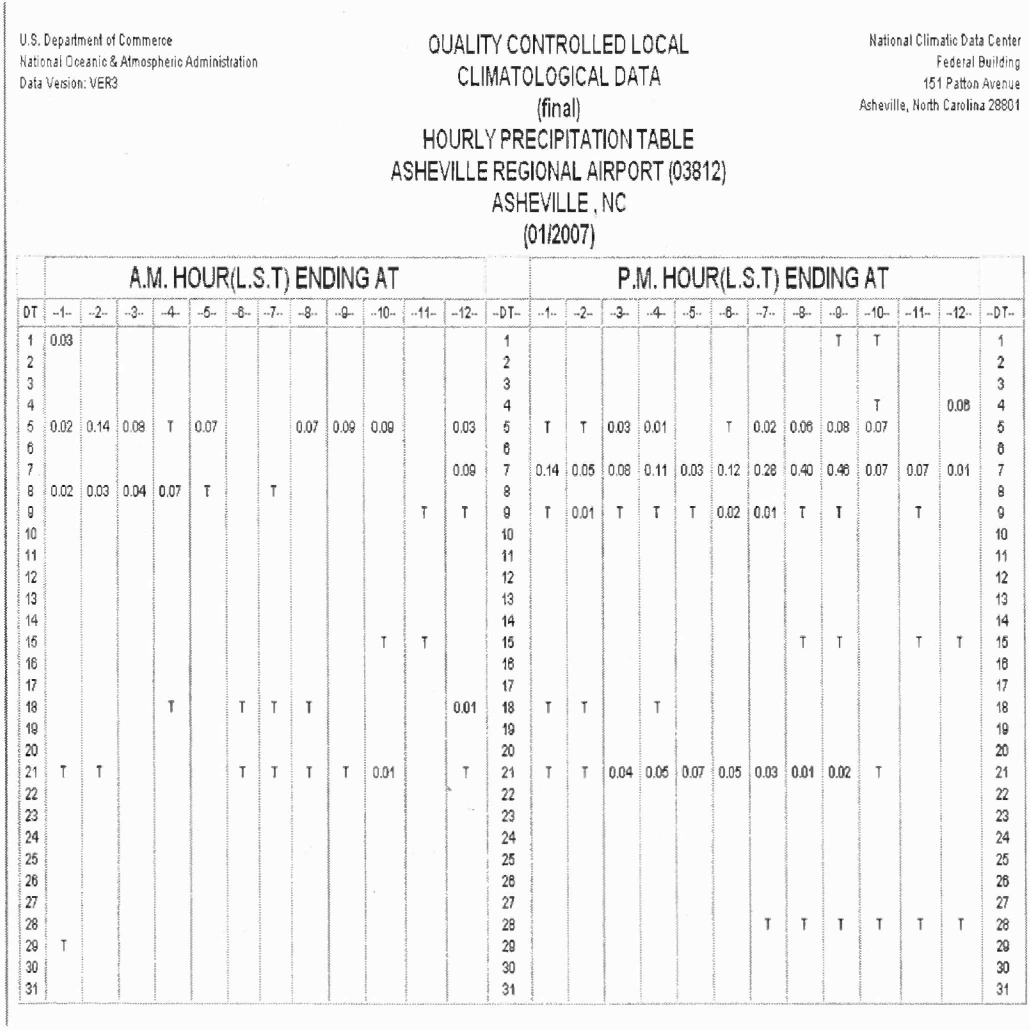
3.1 Introduction

This dissertation analyzes the impact of rain and congested conditions on traffic flow, speed, and capacity for freeways. The results from the research can be used to improve the speed-flow relationships provided in the Highway Capacity Manual (HCM 2000). The results from this research will be useful to transportation system practitioners in evaluating roadway systems under a variety of conditions including rain and congested conditions. For this research weather and traffic data were collected to develop speed-flow relationships. The following provides a description of the weather and traffic data collection and the methodology used to develop speed-flow relationships.

3.2 Data Collection

3.2.1 Weather Conditions Studied

Weather data used in the research were obtained from the National Climatic Data Center (NCDC) website. Rainfall intensity data were obtained on days with rain conditions from NCDC website. The data were considered for study only during the peak period (6–9AM and 4–7PM). Details of each rain event were identified using archived weather databases from the National Climatic Data Center (NCDC). The Center has long served the nation as a national resource of climate information. Rain-related weather events were identified using the National Weather Service's "Hourly Precipitation Data (HPD)" databases. The databases provide hourly precipitation amounts recorded by three rain gauge locations: the National Weather Service, Federal Aviation Administration, and cooperative observer stations. HPD includes maximum precipitation for nine daily periods, ranging in length from 15 minutes to 24 hours for selected stations.

Figure 3.1 shows an example of the hourly precipitation table provided from the National Environmental Satellite, Data, and Information Service. It provides the amount of precipitation for each time period.

U.S. Department of Commerce
National Oceanic & Atmospheric Administration
Data Version: VER3

QUALITY CONTROLLED LOCAL
CLIMATOLOGICAL DATA
(final)
HOURLY PRECIPITATION TABLE
ASHEVILLE REGIONAL AIRPORT (03812)
ASHEVILLE , NC
(01/2007)

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

	A.M. HOUR(L.S.T) ENDING AT													P.M. HOUR(L.S.T) ENDING AT												
DT	--1--	--2--	--3--	--4--	--5--	--6--	--7--	--8--	--9--	--10--	--11--	--12--	--DT--	--1--	--2--	--3--	--4--	--5--	--6--	--7--	--8--	--9--	--10--	--11--	--12--	--DT--
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2													2													2
3													3													3
4													4										T		0.06	4
5	0.02	0.14	0.08	T	0.07			0.07	0.09	0.09		0.03	5	T	T	0.03	0.01		T	0.02	0.06	0.08	0.07			5
6													6													6
7												0.09	7	0.14	0.05	0.08	0.11	0.03	0.12	0.28	0.40	0.46	0.07	0.07	0.01	7
8	0.02	0.03	0.04	0.07	T		T						8													8
9											T	T	9	T	0.01	T	T	T	0.02	0.01	T	T		T		9
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Figure 3.1 Example of Hourly Precipitation (Source: http://cdo.ncdc.noaa.gov/qclcd/QCLCD)

3.2.2 Autoscope

Traffic data were collected using the wide-area detection system Autoscope. In recent years, a number of aboveground technologies have emerged to complement or replace in-ground inductive loops. Inductive loops have limited capabilities, and can fail frequently. These new technologies include video detection, radar, ultrasonic, infrared and laser. Video detection has been the most successful, providing unsurpassed richness of data as well as video images, wider coverage areas and greater versatility of the applications (e.g., wide area detection, accuracy in measuring vehicle counts and speed, detecting stopped vehicles, and reconfiguring the detector to reflect changes in road geometry).

Michalopoulos (1991) stated that the vehicle detection by video cameras is one of the most promising new technologies for wireless large-scale data collection and for implementation of advanced traffic control and management schemes such as vehicle guidance/navigation. Autoscope can work with any camera, and under congested flow while still being able to use the camera for surveillance. Although more work is underway to establish reliability as well as performance on a long-term continuous operation, by all indications the elusive goal of wide-area video detection research and development is now extremely close to fulfillment. The cost-effective ability to detect vehicles via video cameras with satisfactory accuracy for traffic surveillance and control is also achieved. Autoscope should be considered as a wide-area detection system. The Autoscope 2004 System is a full traffic surveillance management system that uses machine-vision technology to produce highly accurate traffic measurements. Each component of the system is essential to the overall process of detecting, calculating, and collecting these types of traffic data:

- Vehicle presence and passage
- Speed
- Average speed
- Density
- Time occupancy
- Incident detection
- Vehicle length
- Space occupancy
- Flow rate
- Volume
- Time headway
- Level of service

An image sensor, or camera, transmits live video signals to an Autoscope machine vision processor (MVP) that processes the images. Figure 3.2 provides a description of this procedure. The MVP then records the results of its analysis.

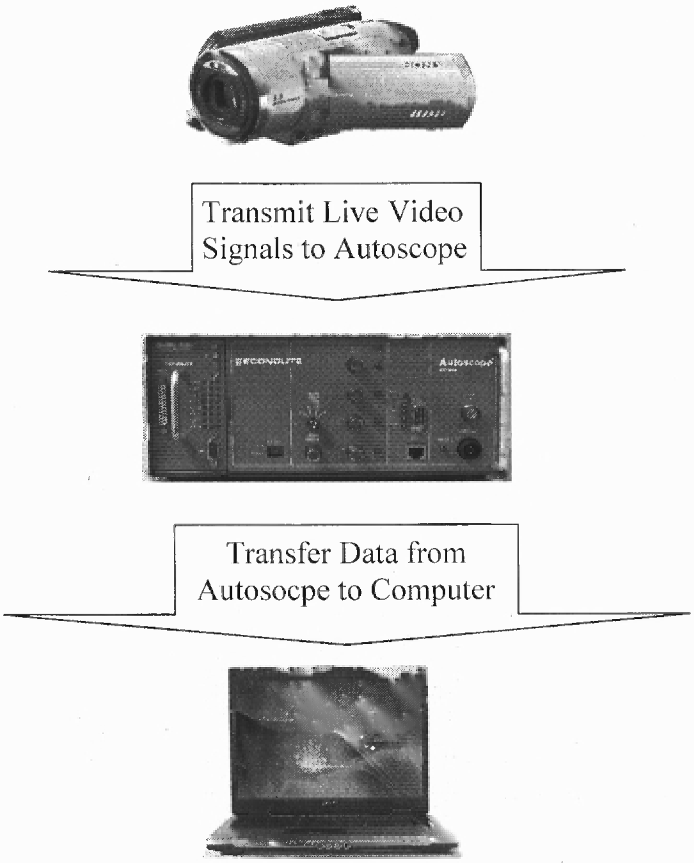

Figure 3.2 Design of Image sensor, MVP, and Computer

The Autoscope Supervisor window is an application window. All software functions can be accessed from this window:

- System installation
- System identification
- MVP operation verification information

3.2.3 Study Locations

To investigate the impact of adverse weather on New Jersey roadways, six New Jersey roadway segments were studied. The locations were selected based on the high traffic flows during the morning peak hour which is from 6:00 to 9:00 AM for model-building and during the evening peak period which is from 4:00 to 7:00 PM for model-validation. They were identified by New Jersey Department of Transportation (NJDOT) and New Jersey Transit (NJ Transit) as roadways impacted by adverse weather conditions. Other sites discussed with NJDOT and NJ Transit was excluded due to difficulties in the obtaining video images at these locations. The data for the study roadways were obtained using a video image recording device (e.g., camcorder) and the video imaging processing system Autoscope 2004. The selected locations and their related geographical information are listed in Table 3.1 and 3.2. To determine the effects of adverse weather conditions, it was essential for the study to collect and analyze an ample amount of traffic volume under various weather conditions. As these locations were not equipped with traffic detectors, data collection equipment was needed to be used. The data were recorded using a video camera from an overpass roadway at each study location. Figure 3.3 shows an example of one study area.

Table 3.1 Study Locations for Model-Building

Sites	**Overpass**	**Time**	**No. of Lane**	**Speed Limit**	**Area**
Rte 46	North Rd	AM (6:00-9:00)	3	50 mph	Essex County
Rte 3	Peterson Plank Rd	AM (6:00-9:00)	4	50 mph	Bergen County
I - 495	Central Ave	AM (6:00-9:00)	3	50 mph	Bergen County
I - 80	Queen Anne Rd	AM (6:00-9:00)	2 for cars 3 for cars/trucks	55 mph	Bergen County

Table 3.2 Study Locations for Model-Validation

Sites	**Overpass**	**Time**	**No. of Lane**	**Speed Limit**	**Area**
I - 78	Hillcrest Rd	PM (4:00-7:00)	3	65 mph	Somerset County
Rte 22	South St	PM (4:00-7:00)	2	40 mph	Union County

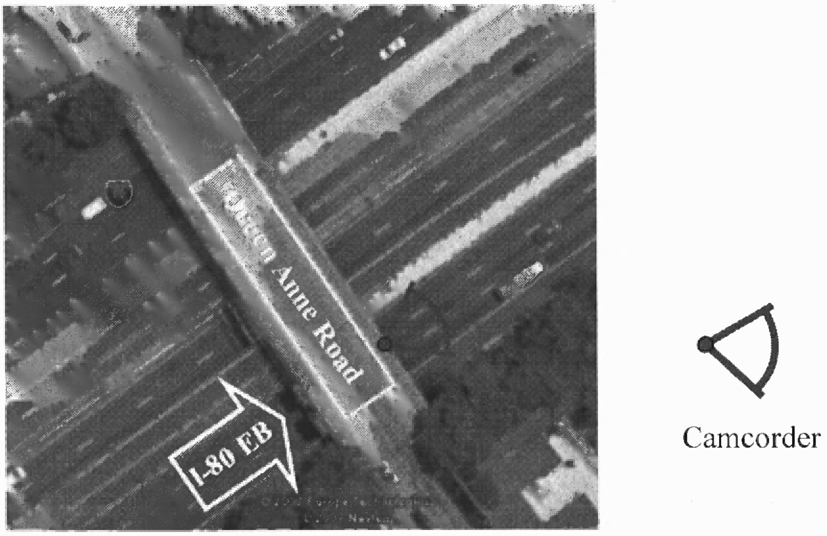

Figure 3.3 Data Collection Location for I-80 (Source: http://maps.google.com)

3.2.4 Descriptions of Study Locations

The following provides a description of each of the study locations.

Route 46 – Notch Road, Clifton

Route 46 is an Urban Principal Arterial roadway located in Essex County. The roadway consists of six lanes with three lanes is each direction and with no parking on either side of the roadway. Route 46 intersects with Valley Road and Route 3 East as shown Figure 3.4.

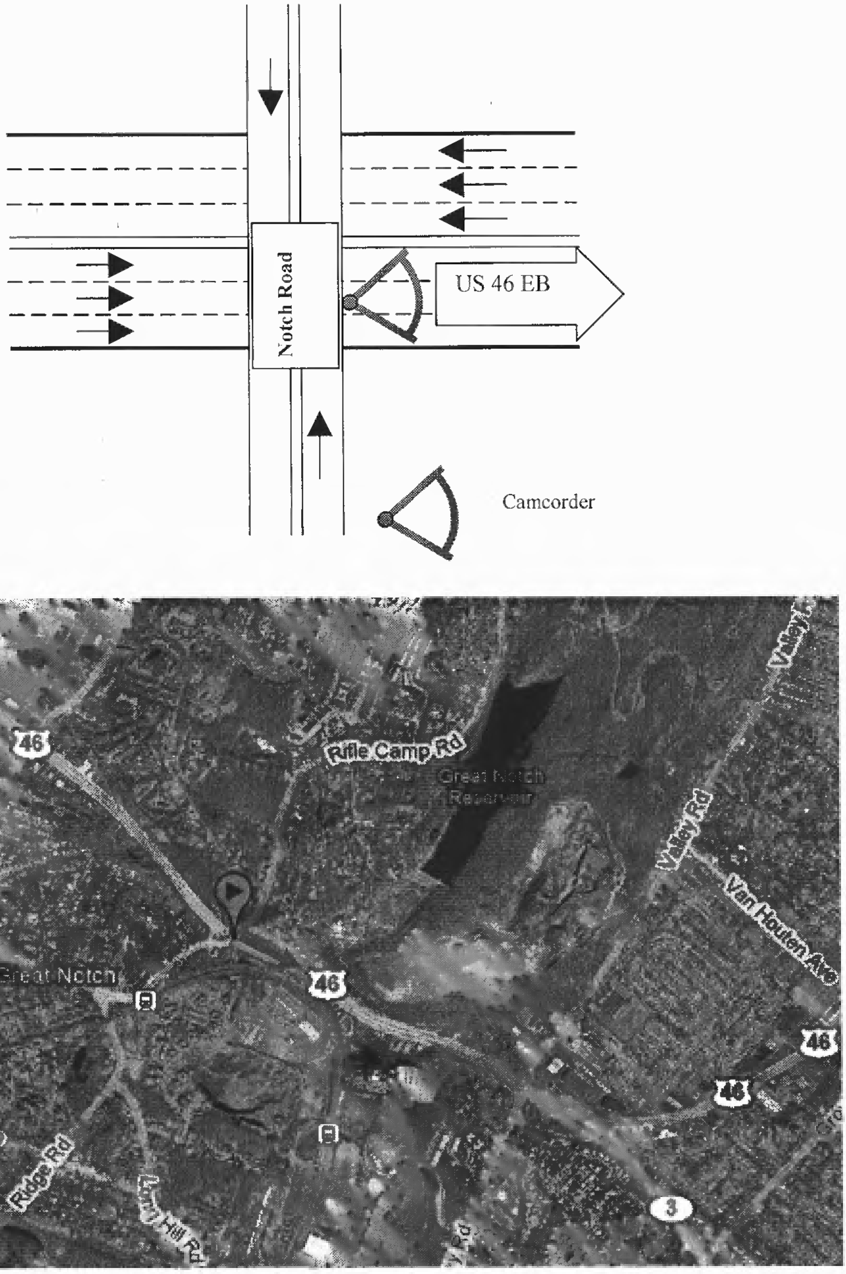

Figure 3.4 Rte 46 Road Structure and Geographic Location (Source: http://maps.google.com)

Figure 3.5 shows the section of Route 46 under study route. As the figure shows, the entrance ramp may add considerable traffic. There is a chance at congested condition may be caused by the impact of the entrance ramp.

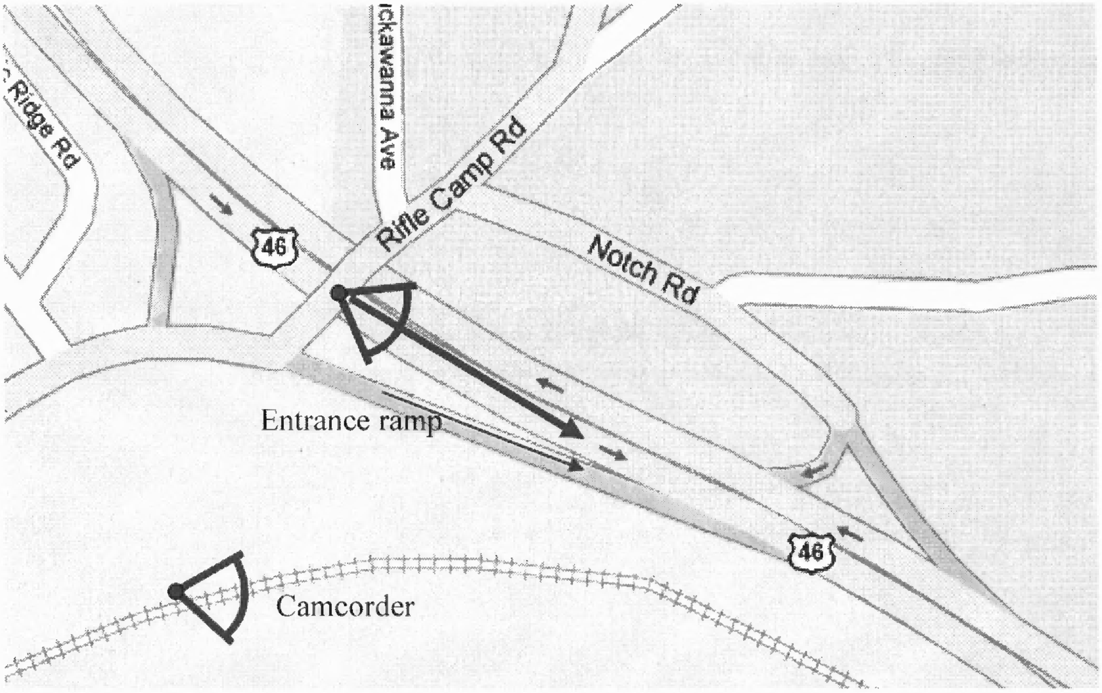

Figure 3.5 Entrance Ramp on Rte 46 (Source: http://maps.google.com)

Route 3 - Paterson Plank Road, Carlstadt

Route 3 is an Urban Freeway/Expressway located in Bergen County. The roadway consists of eight lanes with four lanes is each direction and with no parking on either side of the roadway. Route 3 intersects with Route 1 and I-495 as shown in Figure 3.6.

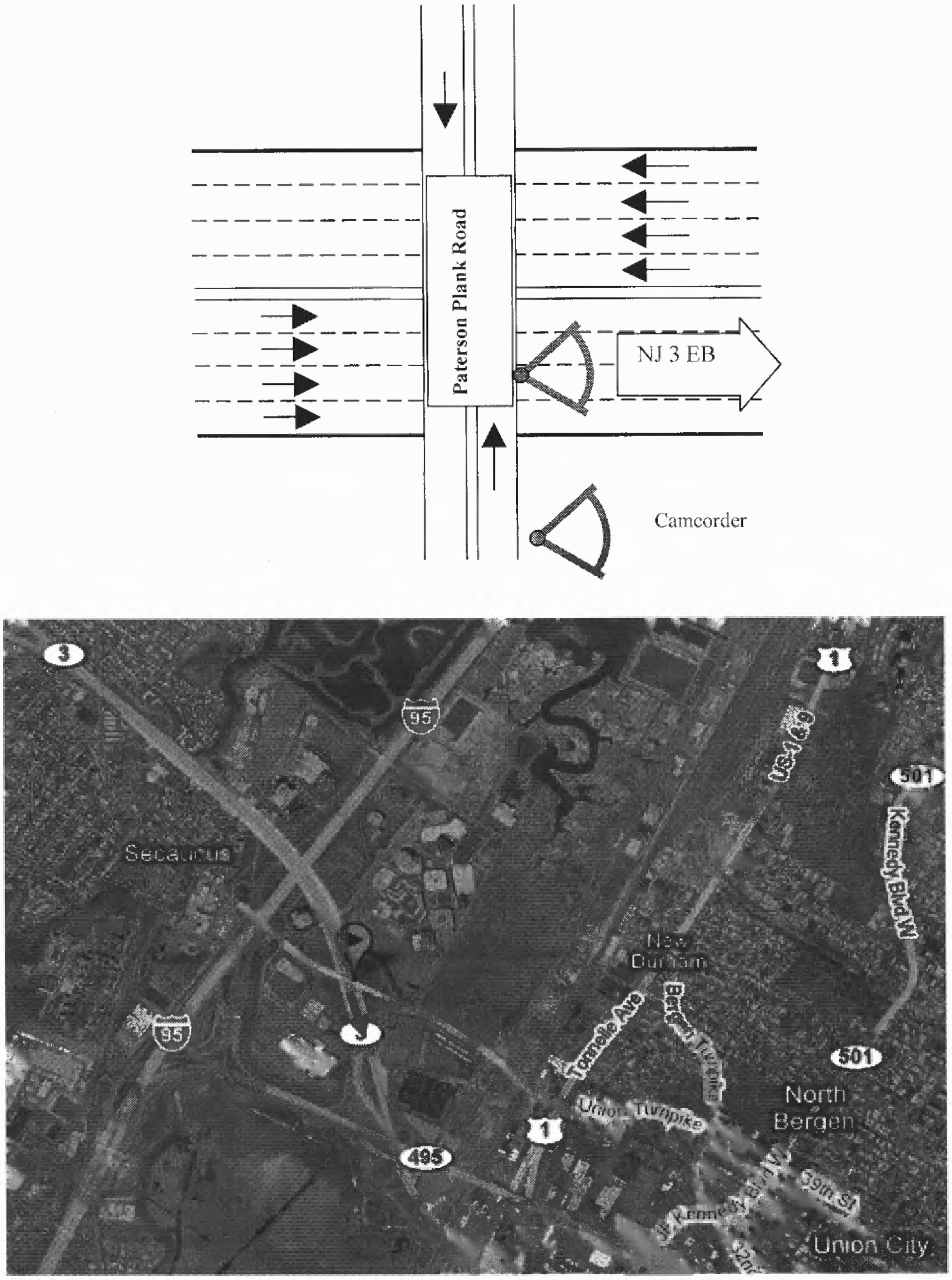

Figure 3.6 Rte 3 Road Structure and Geographic Location (Source: http://maps.google.com)

<u>I-495– Central Ave, Union City</u>

Interstate-495 is an Urban Freeway/Expressway located in Bergen County.

The roadway consists of six lanes with three lanes is each direction and with no parking on either side of the roadway. Figure 3.7 shows the road structure and geographic location of the roadway. This study route provides access to the Lincoln Tunnel, a major tunnel providing access to Manhattan, and has relatively high vehicular volumes causing heavy traffic congestion in the AM peak period.

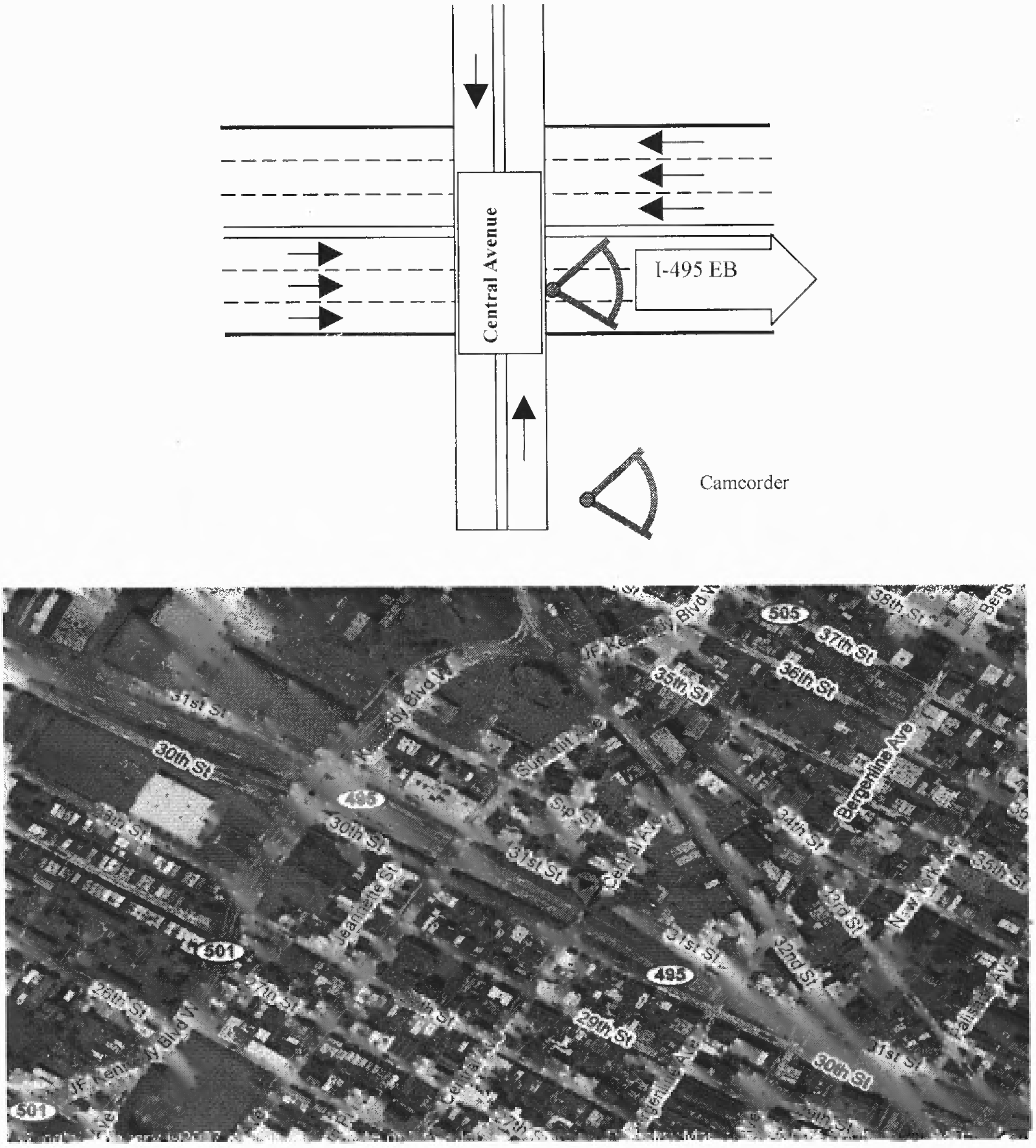

Figure 3.7 I-495 Road Structure and Geographic Location (Source: http://maps.google.com)

I-80 – Queen Ann Road, Bogota

Interstate-80 is an Urban Interstate located in Bergen County. The roadway consists of three lanes for cars and two lanes for cars/trucks with a total of five lanes is each direction and with no parking on either side of the roadway. Figure 3.8 shows the Interstate-80 accesses to Interstate-95.

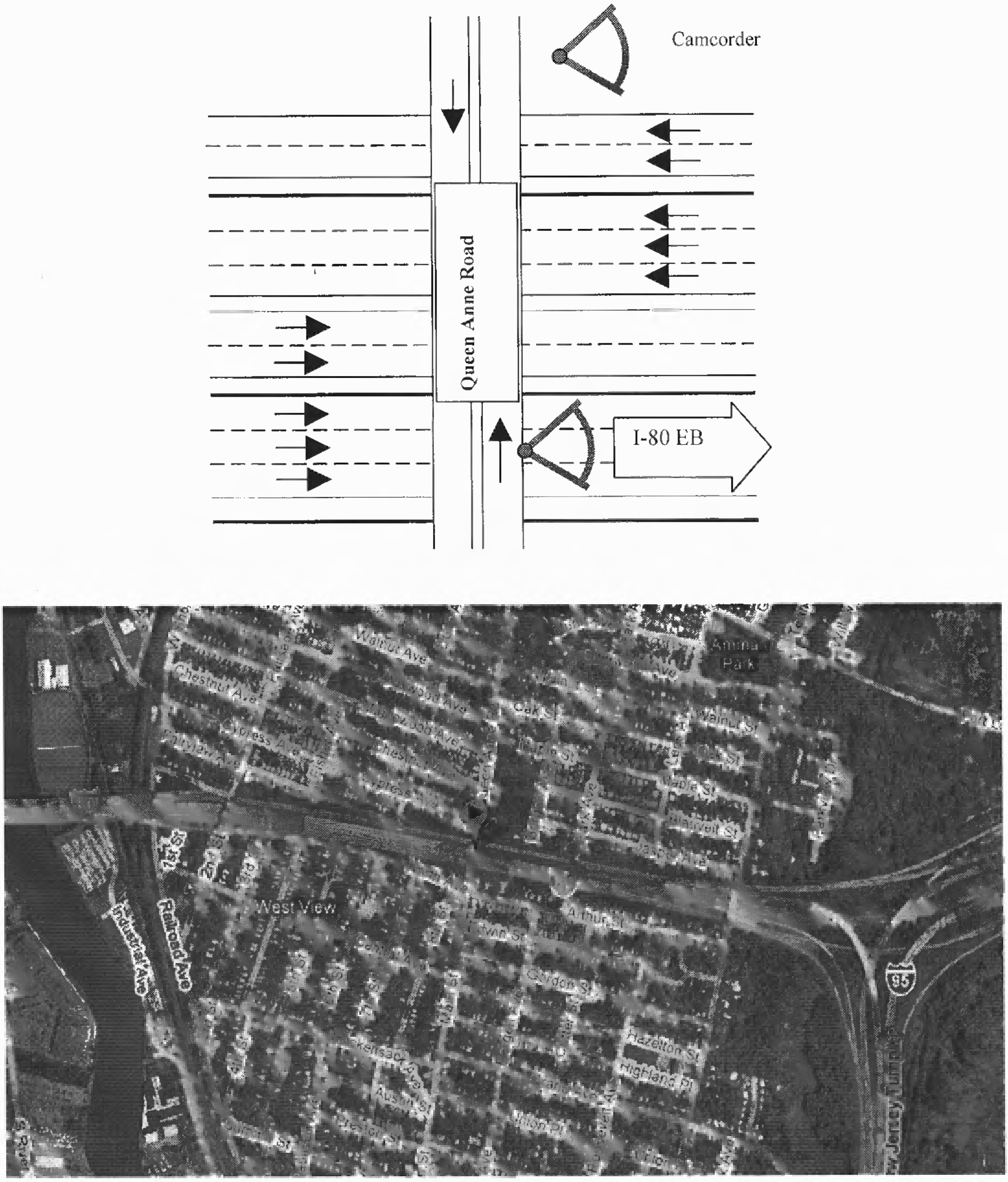

Figure 3.8 I-80 Road Structure and Geographic Location (Source: http://maps.google.com)

I-78 – Hillcrest Road, Watchung

I-78 is an Urban Interstate located in Somerset County. The roadway consists of six lanes with three lanes is each direction and with no parking on either side of the roadway as shown in Figure 3.9.

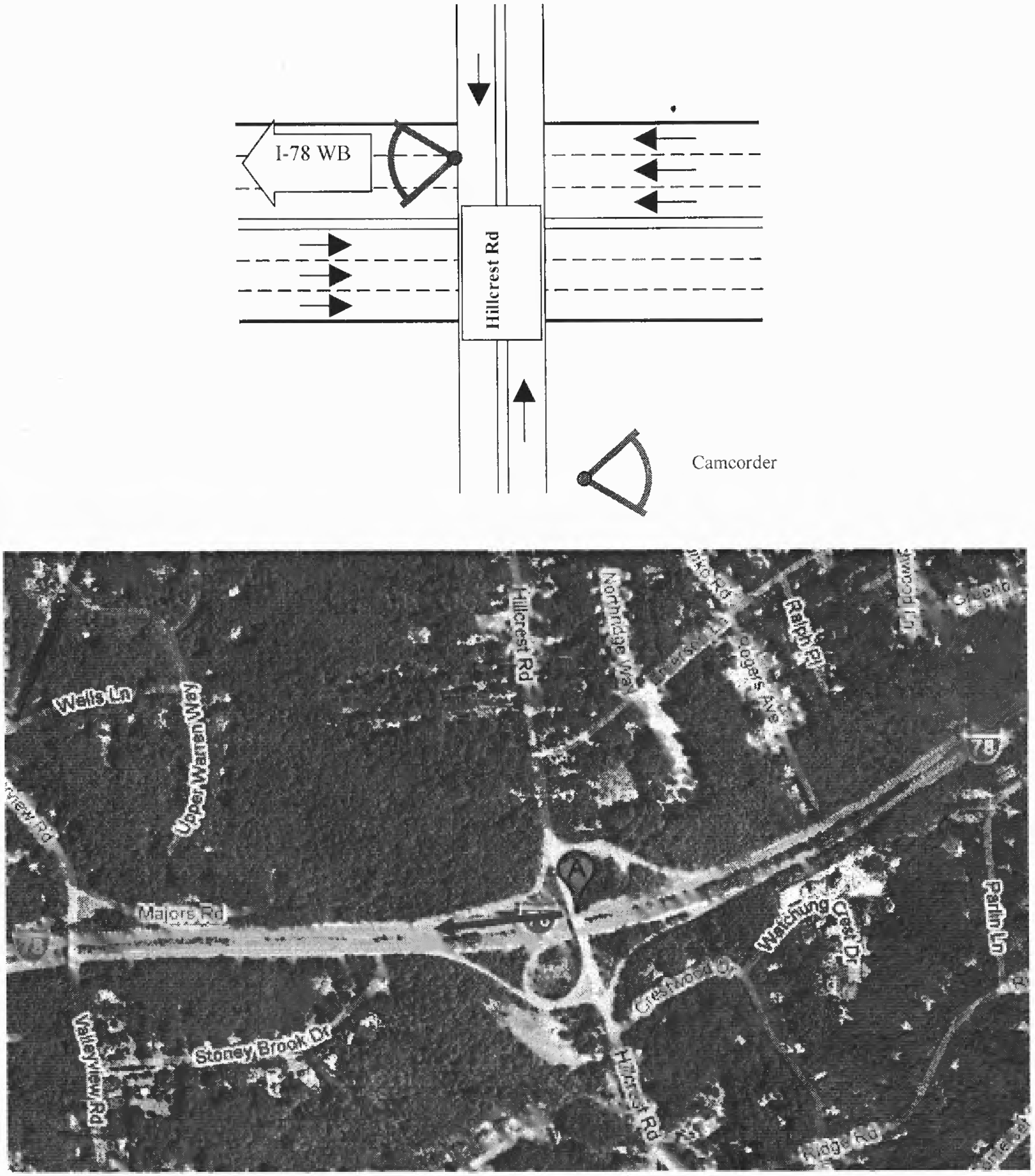

Figure 3.9 I-78 Road Structure and Geographic Location (Source: http://maps.google.com)

Rte 22 – South Street, Hillside

Route 22 is an Urban Principal Arterial roadway located in Union County. The roadway consists of four lanes with two lanes is each direction and with no parking on either side of the roadway as shown in Figure 3.10.

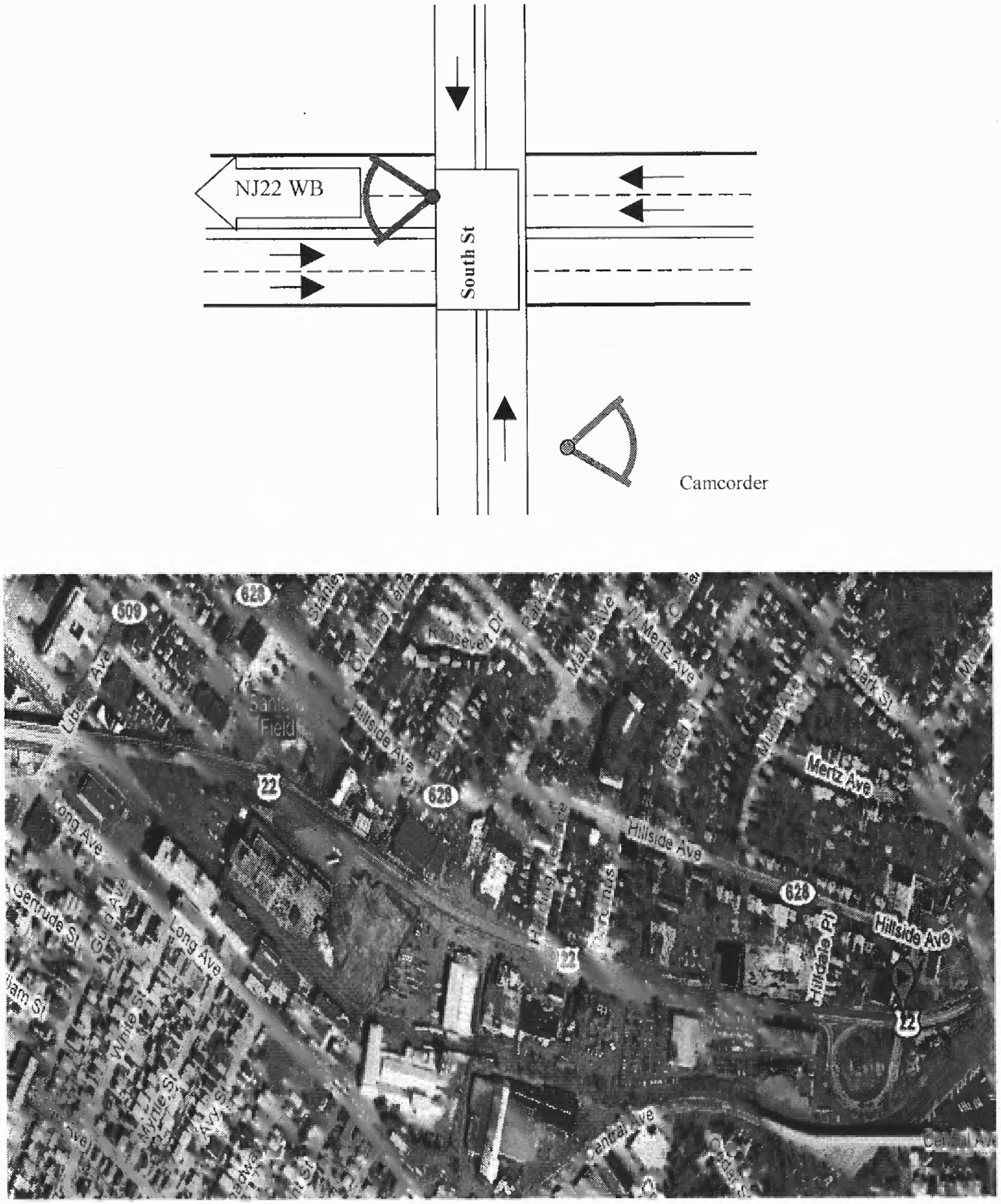

Figure 3.10 Rte 22 Road Structure and Geographic Location (Source: http://maps.google.com)

3.3 Summary of Data Collected

One of the objectives of this research is to estimate speed-flow relationships under normal and rain conditions. To address this objective, speed and flow data were collected at each of the study locations under normal and rain conditions. And comparisons were made between speed and flow under no adverse weather conditions, referred to as normal conditions and rain conditions. The data sets for the peak period included a varied range of speed and flow conditions. During the study, it was important to include days with different types of weather conditions with varied intensities. Table 3.3 shows the data collection summary for this study. Data were collected for 22 days under normal and rain: two weather conditions.

A total of 6 hours under normal conditions and 6 hours under rain conditions were collected at each location except for I-495. A total of 12 hours under congested conditions were collected at Route 46, I-495 and Route 22. In total, at the six study locations, 66 hours of data were collected. The rain intensity ranged from 0.01 inches/hr to 0.24 inches/hr. The traffic flow data consists of 180 1-minute intervals of speed and flow for each day and each study location generating a total of 3960 data. The data are available for each lane and for the average of all lanes within each study location. The average speed and flow data over all lanes for a 1-minute time interval is used in this study.

Table 3.3 Data Collection Summary

Locations	Date		Rain Intensity (inches/hr)		
	Normal[a]	**Rain**	**6-7 AM**	**7-8 AM**	**8-9AM**
Rte 46	12/13/06	01/08/07[b]	0.12	0.11	0.05
	12/22/06	10/25/07	0.07	Trace[c]	Trace[c]
Rte 3	02/23/07	10/25/07	0.07	Trace[c]	Trace[c]
	09/14/07	02/13/08	0.23	0.22	NA
I-495	01/22/07[b]	04/27/07[b]	Trace	0.22	0.21
I-80	12/13/06	04/16/07	0.16	0.24	0.24
	01/25/07	10/25/07	0.05	Trace[c]	NA
			4-5 PM	**5-6 PM**	**6-7PM**
I-78	09/18/07	02/01/08	0.01	0.16	0.06
	10/16/07	02/13/08	0.02	0.01	Trace[c]
NJ 22	11/20/06[b]	02/26/08	0.02	0.03	0.06
	11/21/06	03/19/08	0.09	0.06	0.08

a: normal condition refers to conditions with no adverse weather
b: congested condition - which refer to be characterized by slower speeds and queueing
c: Trace refer to precipitation amount is less than 0.01 inches/hr

3.4 Speed-Flow Model Development

3.4.1 Regression Analysis

Regression analysis is a statistical methodology that utilizes the relation between two or more quantitative variables so that a response or outcome variable can be predicted from the independent variables (Kutner, 2004). It is used for predicting the response of the outcome variable of interest. Three assumptions must hold when building a regression model. First, the dependent variable must be continuous. Second, the data being modeled meets the "iid" criterion, meaning that the error terms, ε, are independent from one another and identically distributed. Third, the error term is normally distributed with a mean of zero and a standard deviation of σ^2, N $(0, \sigma^2)$.

The regression model is a formal means of expressing the tendency of the response variable, speed, to vary with the predictor variable, flow rate, in a systematic fashion. Conventionally the confidence intervals for regression models are usually calculated for the 95% confidence level.

3.4.2 Regression Model Form

One question considered in the development of the speed-flow model is whether the regression model form should be forced through the origin. The question about whether to force the equation through the origin is a legitimate question despite the long-standing convention that the speed-flow curve is continuous all the way to the origin under congested conditions. In traffic flow theory, it has always been understood that the speed-flow curve must pass through the origin because during jam conditions, both flow and speed are zero. The data set obtained for this research did not include any flows below 600 vphpl since this flow rate would only be observed unless there was a major accident during the peak period. It is hard to envision situations in which average flow rates of less than 400 vphpl can be found during the peak period.

Different options in predictor variables determine the functional form of the regression variables. The appropriate functional form may be determined experientially or theoretically. For example, the speed-flow relationship typically is nonlinear in nature, characterized by a rapid speed reduction when the flow rate increases as it reaches a maximum capacity under normal conditions. Under congested conditions, the average speed increases fast as the flow rate increases.

In this research, four functional regression forms of the speed-flow relationship were considered. With speed build up the dependent variable and flow rate the independent variable. Four functional regression forms were compared to identify the best fitting model. The models considered include a linear, quadratic, exponential, and logarithmic function. The linear model is stated as $S = aF + b$. S is denoted as 'Speed' and F is denoted as 'Flow rate.' The linear function consists of an intercept, b, and a slope which is the coefficient of the flow rate, a. For a speed-flow relationship, the intercept defines the speed when the flow rate is zero. The slope defines the change in the speed divided by the corresponding change in the flow rate. These equations are called "linear" because they represent straight lines.

The quadratic model is stated as $S = aF^2 + bF + c$ or $S = aF^2 + c$. The quadratic function is a polynomial equation of the second degree which consists of quadratic term, linear term, and intercept. If the p values of quadratic and linear terms are greater than 0.05, Zhou and Hall (1999) stated that the linear term of the quadratic form could be dropped and the reduced model might be used.

The exponential model is stated as $S = ae^{bF}$ or $S = ae^{bF} + c$. The exponential function is an equation which is in the form $e^{Flow\ rate}$, where *e* is a mathematical constant, the base of the natural logarithms. The speed-flow relationship of Speed = $e^{Flow\ rate}$ is always positive (above the flow rate axis) and increasing (viewed left-to-right). Its inverse function, the natural logarithm equation, ln(*Flow rate*), is defined for all positive Flow rates. The logarithmic model is stated as $S = a\ln(F) + b$.

The regression model using the combined roadways

To test whether all data can be explained in one function, dummy regression variables were used. An advantage of using model with a dummy variable is that one regression run will yield both fitted regressions. Another advantage is that tests for comparing the regression functions for the different classes of the qualitative variable can be clearly seen to involve tests of regression coefficients in a general model.

Each normal, rain, congested condition was considered as potentially a separate class and a different effect. Using the data of combined roadways, the dummy variable regression was used for congested conditions. The dummy variable with the values of 1 and 0 is to distinguish between two data sets: for example, the differences between normal and congested conditions (the dummy of congestion = 0 for congestion, 1 otherwise). The congested condition is characterized by slow speeds and queueing. A road in a constant traffic jam would be below LOS F in Highway Manual (HCM 2000) when the average density is greater than 45 vpmpl.

The regression equation using the combined roadways may have a problem of multicollinearity when the regression form includes a dummy variable. The value of b, which is an exponential form as $S = ae^{bF} + c$ for congested conditions, is used 0.002 and avoided the problem of multicollinearity using the combined roadways data in this research. The variance inflation factor (VIF) is n indicator that detects the severity of multicollinearity which measures how much the variance of a coefficient (square of the standard deviation) is increased because of collinearity. Two or more predictor variables in a multiple regression model are highly correlated when the VIF is greater than 5.

Multicollinearity is also present when flow rate is a dependent variable and speed is an independent variable in speed-flow regression model.

The continuous variable regression is used for the rain intensities. If the model is stated as $S = aF^2 + b$ under normal conditions and $S = cF^2 + d$ under rain conditions, the model for both normal and rain conditions is stated as $S = aF^2 + b + P(cF^2 + d)$ using P to represent the precipitation levels. When precipitation is 0.1 inches/hr, the model for both normal and rain conditions is:

$S = aF^2 + b + P(cF^2 + d) = (a + cP)F^2 + b + dP = (a + 0.1c)F^2 + b + 0.1d$.

3.4.3 Identification of the Variables in Speed-Flow Model

To identify the variables to be included in the speed-flow regression models the t statistics, their associated p-value, and the variance inflation factor was used. The procedure begins with the model containing all potential independent variables. If the maximum p value is greater than a predetermined limit, 0.05 significant level in this case, that dependent variable is dropped. The regression routine fits a regression model for each of the potential independent variables. The t statistic used for testing whether or not the slope of the variable is zero is obtained from Equation 4.10.

$$t = \frac{b_k}{s\{b_k\}} \tag{4.10}$$

where: b_k is coefficient of k^th^ dependent variable for k=1,……, p-1

$s\{b_k\}$ is standard error of kth dependent variable

The dependent variable with the largest t value is the candidate for inclusion in the regression equation. The null hypothesis used to test whether the slope is zero is stated as $\beta_k=0$ and the alternative hypothesis is stated as $\beta_k\neq0$. The decision rule is: if $|t| \leq t\left(1-\frac{\alpha}{2};n-k\right)$, then conclude H_0, the null hypothesis, otherwise conclude H_a, alternative hypothesis. This process continues until no further dependent variables can be dropped. The independent variables that are considered essential should be included in the regression model.

CHAPTER 4

ANALYSIS

One of the goals of this research was to develop speed-flow relationships that could be used for predicting speed under normal and rain conditions. Regression analysis was used to develop speed-flow relationships under normal and rain conditions. Data gathered on roadways were used, if they showed reasonable results and there was not an impact from downstream capacity constraints that would impact the measurement of speed at the study location. Four functional forms of the regression model were used including: linear, quadratic, logarithmic, and exponential curves. The following provides a discussion of the speed-flow models developed.

Statistical analyses were performed to study the effects of rain and congested conditions on speed-flow relationships for freeways in New Jersey. The analysis developed the speed-flow relationships for each weather condition and roadway studied including normal, rain, and congested conditions for each location. A speed-flow relationship was also developed using data for the combined roadways. The results determined the impact of rain and congestion on speed and flow conditions. The data were aggregated to 1- and 5-minute intervals as differences which are not significant when using 1-minute data become significant when using 5-minute data. As 5-minute data have lower variability, the aggregation reduces the scatter of the data. The 1-minute data used in this study were:

- Data for each roadway under normal, rain, or congested conditions separately;
- Data for each roadway under all weather and congested conditions; and
- Data for combined roadways under all weather and congested conditions

Using the data collected, speed, flow and density were determined under normal, rain, and congested condition. Tables 4.1 through 4.5 show a summary of the speed, density and flow data collected for each location and the impact of rain and congestion. The following paragraphs describe the impact of weather on each roadway.

Overall, under normal conditions the average speed ranges from 51.78 mph on I-495 to 65.25 mph on I-80. The average speed is reported for each of the two days of data in Table 4.1. In general, there are small differences between the average speeds between the two days of data. The difference between the average speeds for two days of data ranges from 0.24 mph at I-80 to 4.86 mph at Route 46. The speed ranges from 51.78 mph on I-495 to 65.25 mph on I-80, the flow rate ranges from 1043 vphpl on Route 46 to 1519 vphpl on Route 3 and the density ranges from 16.61vpmpl on Route 46 to 24.7 vpmpl on Route 3. The minimum and maximum density and flow rates are on Route 46 and Route 3, respectively.

Under rain conditions, speed decreases between 5.82 mph at I-80 with a rain intensity of 0.02 inches/hr and 19.65 mph at Route 3 with a rain intensity of 0.22 inches/hr. The flow rate decreases by 364 vphpl at I-80 with a rain intensity of 0.20 inches/hr and increases by 299 vphpl at Route 46 with a rain intensity of 0.02 inches/hr. The density increases by 0.89 vpmpl at I-80 with a rain intensity of 0.20 inches/hr and by 17.11 vpmpl at Route 46.

Between normal-congested and rain-congested conditions speed decreases 3.65 mph, flow rate decreases by 5 vphpl, and density increases by 17.77 vpmpl at I-495 with a rain intensity of 0.21 inches/hr. Between normal and normal-congested conditions speed decreases 28.56 mph, flow rate increases by 395 vphpl, and density increases by 48.88 vpmpl at I-495.

At Route 46, the average speed under normal conditions varies from 58.49 mph to 63.35 mph with an average speed over the two days of 61.15 mph. At this location speed data were gathered under low (0.02 inches/hr) to moderate rain intensity (0.11 inches/hr). Under low rain intensity, the average speed is 48.49 mph. Under low/moderate rain intensity, the average speed is 23.47 mph which is significantly lower than the average speed under normal conditions. The rain impact under low rain intensity is 12.66 mph.

At Route 3, the average speed under normal conditions over the two days is 62.16 mph. At this location speed data were gathered under low rain intensity (0.03 inches/hr) and moderate to heavy rain intensity (0.22 inches/hr). Under low rain intensity, the average speed is 50.17 mph and under moderate/heavy rain the average speed is 42.51 mph. The rain impact under low rain intensity is 11.99 mph and 19.65 mph under moderate/heavy rain intensity.

At I-495, the average speed under normal conditions is 51.78 mph and under congested conditions is 23.22 mph. At this location speed data were gathered under moderate to heavy rain intensity (0.21 inches/hr). Under moderate/heavy rain the average speed is 19.57 mph. The rain impact is the speed reduction of 3.65 mph under moderate/heavy rain intensity from normal-congested to rain-congested conditions.

At I-80, the average speed under normal conditions varies from 64.98 mph to 65.22 mph for an average speed over the two days of 65.25 mph. At this location speed data were gathered both under low rain intensity (0.02 inches/hr) and moderate and heavy rain intensity (0.20 inches/hr). Under low rain intensity, the average speed is 59.43 mph and under heavy rain the average speed is 52.77 mph. This speed reduction is referred to in Table 4.3 and 4.4 as the "rain impact" and as the "congestion impact" in Table 4.5.

Tables 4.6 through 4.8 show the impact of rain and congestion on headway. Under rain conditions, space headway decreases between 3.8% at I-80 with a rain intensity of 0.20 inches/hr to 47.2% at Route 46 with a rain intensity of 0.02 inches/hr. Time headway increases 18.9% at I-80 and decreases 33.4% at Rte 46. From normal-congested to rain-congested conditions, space headway decreases 20% at I-495 with a rain intensity of 0.21 inches/hr. From normal to normal-congested conditions, space headway decreases 69% at I-495.

Table 4.1 Summary of Traffic Parameters under Normal Conditions

	Weather	Date or Precipitation	Average Speed	Stdev of Speed	Average Flow rate	Stedv of Flow rate	Average Density	Stedv of Density
Rte 46	Normal	12/13/06	58.49	3.26	1258	292	22.08	5.94
	Normal	12/22/06	63.35	3.54	1043	242	16.61	4.35
	Normal	12/13+12/22	61.15	4.03	1152	289	19.12	5.71
	Rain	0.02 inches/hr	48.49	13.14	1451	272	36.23	24.90
Rte 3	Normal	02/23/07	62.37	2.31	1486	260	24.52	4.92
	Normal	09/14/07	61.79	2.42	1519	236	24.70	4.34
	Normal	02/23+09/14	62.16	2.39	1502	249	24.27	4.52
	Rain	0.03 inches/hr	50.17	4.53	1662	230	39.83	8.07
	Rain	0.22 inches/hr	42.51	2.81	1508	181	35.73	5.55
I-495	Normal	01/22/07	51.78	3.62	1096	164	21.38	4.24
I-80	Normal	12/13/06	64.98	3.07	1492	253	23.72	4.91
	Normal	10/15/07	65.22	3.49	1396	244	21.55	4.46
	Normal	12/13+10/15	65.25	3.28	1444	253	22.28	4.58
	Rain	0.02 inches/hr	59.43	4.86	1434	212	25.17	4.81
	Rain	0.20 inches/hr	52.77	8.80	1080	463	23.17	8.30

Table 4.2 Summary of Traffic Parameters under Congested Conditions

	Weather	Date or Precipitation	Average Speed	Stdev of Speed	Average Flow rate	Stedv of Flow rate	Average Density	Stedv of Density
I-495	Normal	01/22/07	23.22	8.27	1491	275	70.26	19.26
	Rain	0.21 inches/hr	19.57	9.16	1486	336	88.03	28.74
Rte 46	Rain	0.11 inches/hr	23.47	7.52	1326	184	60.45	14.47

Table 4.3 Rain Impact between Normal and Rain Conditions

	Precipitation	Average Speed	Stdev of Speed	Average Flow rate	Stedv of Flow rate	Average Density	Stedv of Density
Rte 46	0.02 inches/hr	-12.66(-21%)	9.11(226%)	299 (26%)	-17 (-6%)	17.11(89%)	19.19(336%)
Rte 3	0.03 inches/hr	-11.99(-19%)	2.14 (90%)	160 (11%)	-19 (-8%)	15.56(64%)	3.55 (79%)
	0.22 inches/hr	-19.65(-32%)	0.42 (18%)	6(0.4%)	-68(-27%)	11.46(47%)	1.03 (23%)
I-80	0.02 inches/hr	-5.82 (-9%)	1.58 (48%)	-10 (-1%)	-41(-16%)	2.89(13%)	0.23 (5%)
	0.20 inches/hr	-12.48(-19%)	5.52(168%)	-364 (-25%)	210(-83%)	0.89(4%)	3.72(81%)

Table 4.4 Rain Impact between Normal-Congested and Rain-Congested Conditions

	Precipitation	Average Speed	Stdev of Speed	Average Flow rate	Stedv of Flow rate	Average Density	Stedv of Density
I-495	0.21 inches/hr	-3.65(-16%)	0.89(11%)	-5(-0.3%)	61(22%)	17.77(25%)	9.48(49%)

Table 4.5 Congestion Impact between Normal and Normal-Congested Conditions

	Date	Average Speed	Stdev of Speed	Average Flow rate	Stedv of Flow rate	Average Density	Stedv of Density
I-495	1/22/07	-28.56(-55%)	4.65(128%)	395(36%)	111(68%)	48.88(229%)	15.02(354%)

Table 4.6 Rain Impact of Headway between Normal and Rain Conditions

	Precipitation	Headway	(mi/veh)	Headway	(sec)	Headway	(ft/veh)
Rte 46	0.02 inches/hr	-0.052	-47.2%	-1.03	-33.4%	-130.42	-47.2%
Rte 3	0.03 inches/hr	-0.016	-39.1%	-0.58	-24.5%	-84.99	-39.1%
	0.22 inches/hr	-0.013	-32.1%	-0.02	-0.7%	-69.78	-32.1%
I-80	0.02 inches/hr	-0.005	-11.5%	-0.017	-2.8%	-27.21	-11.5%
	0.20 inches/hr	-0.002	-3.8%	0.47	18.9%	-9.10	-3.8%

Table 4.7 Rain Impact of Headway between Normal-Congested and Rain-Congested Conditions

	Precipitation	Headway	(mi/veh)	Headway	(sec)	Headway	(ft/veh)
I-495	0.21 inches/hr	-0.003	-20.2%	-0.12	-5.3%	-15.17	-20.2%

Table 4.8 Congestion Impact of Headway between Normal and Normal-Congested Conditions

	Date	Headway	(mi/veh)	Headway	(sec)	Headway	(ft/veh)
I-495	1/22/07	-0.033	-69.6%	-1.05	-32.1%	-171.81	-69.6%

4.1 Speed-Flow Models under Normal Conditions

Sections 4.1 to 4.3 describe the speed-flow relationships for each roadway under normal, rain, and congested conditions separately. Figures 4.1 to 4.4 show that the speed-flow models for Route 46, I-495, Route 3, and I-80 respectively, under normal conditions.

4.1.1 Normal Conditions for Route 46

For Route 46, the speed range is 23.32 mph with a minimum speed of 50.93 mph and a maximum speed of 74.25 mph. The flow rate range is between 560 and 2000 vphpl with a difference of 1440 vphpl. Figure 4.1 shows the speed-flow relationships using a quadratic regression curve because the R^2 of the quadratic regression curve is greater than the R^2 of the linear, logarithmic, and exponential regression curves as indicating in Table 4.9. Table 4.9 show the R^2 and the coefficients of the linear, quadratic, logarithmic, and exponential regression curves. The quadratic model can be represented as the reduced model that is stated as $S = aF^2 + c$ because the p values of the linear and quadratic terms are greater than 0.05.

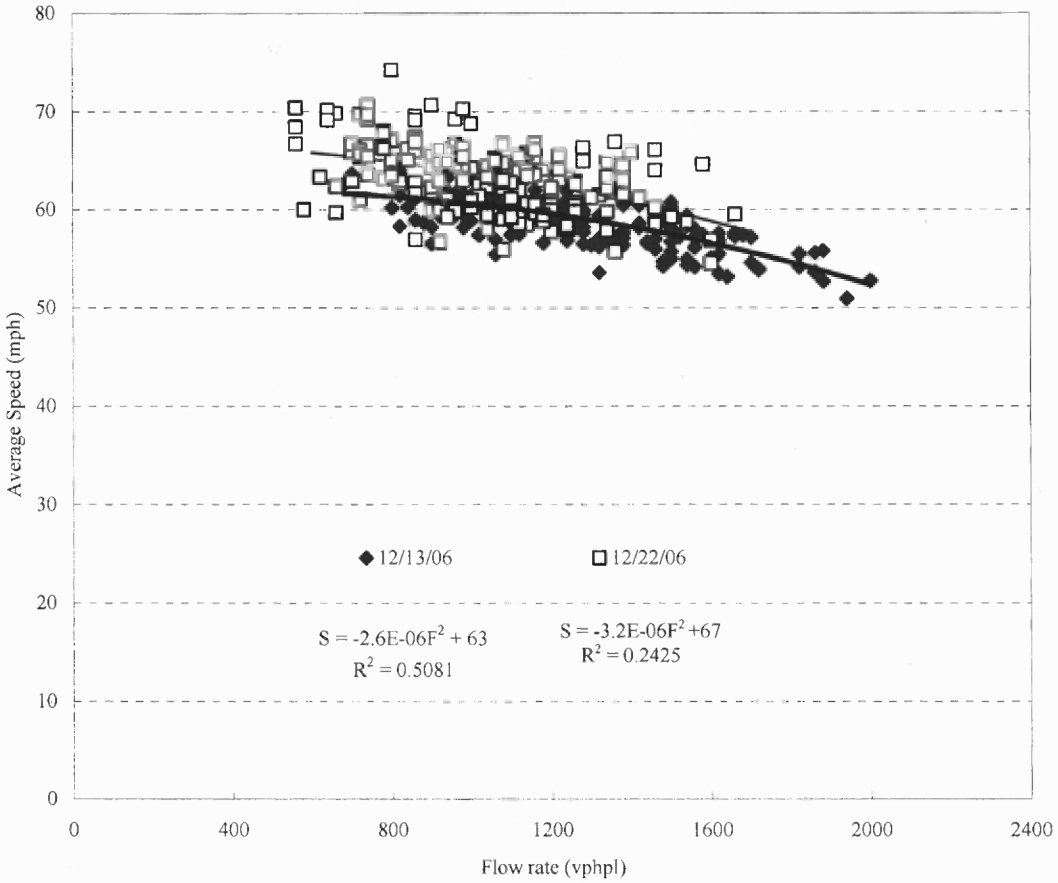

Figure 4.1 Speed-Flow Curves on Rte 46 under Normal Conditions

The R^2 for the Dec. 13 data is greater than the R^2 for the Dec. 22 data. The smaller difference between the speed of raw data and the predicted speed, which is an error term of the regression model, makes the Dec. 13 a better fitting model. The R^2 coefficient of determination indicates how well the regression line approximates the real data points. An R^2 of 1.0 indicates that the regression line perfectly fits the data.

Table 4.9 Speed-Flow Regression Model for Rte 46 – Normal

Regression form	Date	R^2	Regression Equations
Linear	12/13/06	0.49	$S = -0.0068F + 67.5$
	12/22/06	0.24	$S = -0.0071F + 70.8$
	Combined data of 12/13 and 12/22	0.42	$S = -0.009F + 71.5$
Quad	12/13/06	0.51	$S = -0.0000026F^2+63$
	12/22/06	0.24	$S = -0.0000032F^2+67$
	Combined data of 12/13 and 12/22	0.42	$S = -0.0000037F^2+66$
Logarithm	12/13/06	0.46	$S = -8.276\mathrm{Ln}(F) + 117.81$
	12/22/06	0.24	$S = -7.234\mathrm{Ln}(F) + 113.4$
	Combined data of 12/13 and 12/22	0.41	$S = -10.004\mathrm{Ln}(F) + 131.3$
Expo	12/13/06	0.49	$S=68.3e^{-0.0001F}$
	12/22/06	0.23	$S=71.1e^{-0.0001F}$
	Combined data of 12/13 and 12/22	0.42	$S=72.3e^{-0.0001F}$

4.1.2 Normal Conditions for Route 3

For Route 3, the speed range is 16.92 mph with a minimum speed of 54.1 and a maximum speed of 71.02 mph. The flow rate range is between 820 and 2240 vphpl with a difference of 1420 vphpl. The range of the average speed on Route 3 is slightly greater than that Route 46. Figure 4.2 shows a speed-flow relationships using a quadratic regression curve because the R^2 of the quadratic regression curve is greater than the R^2 of the linear, logarithmic, and exponential regression curves as shown in Table 4.10.

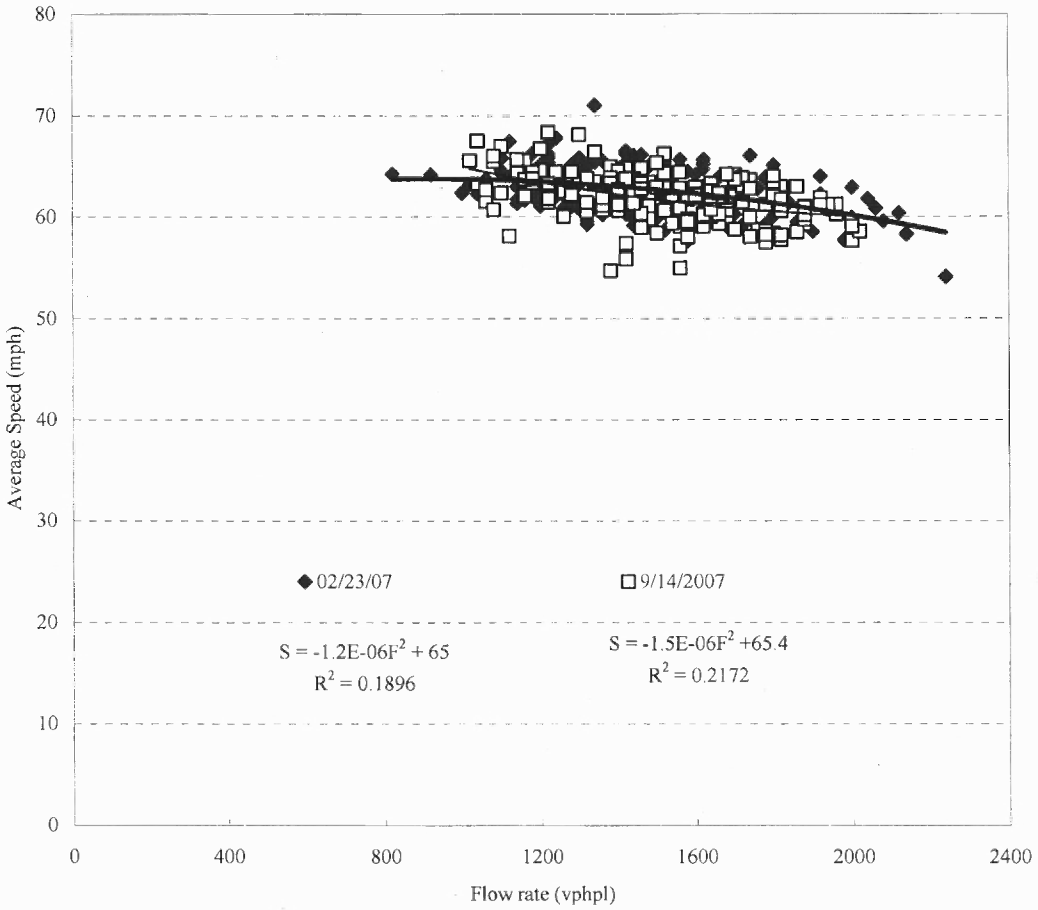

Figure 4.2 Speed-Flow Curves on Rte 3 under Normal Conditions

Table 4.10 shows the R^2 and the coefficients of the linear, quadratic, logarithmic, and exponential regression curves. The R^2 of Sept.14 is greater than the R^2 of Feb.23.

Table 4.10 Speed-Flow Regression Model for Rte 3 – Normal

Regression form	Date	R^2	Regression Equations
Linear	02/23/06	0.17	$S= -0.0037F+ 68$
	09/14/07	0.22	$S= -0.0048F+ 69$
	Combined data of 02/23 and 09/14	0.20	$S= -0.0043F+ 69$
Quad	02/23/06	0.19	$S = -0.0000012F^2+ 65$
	09/14/07	0.22	$S = -0.0000015F^2+ 65$
	Combined data of 02/23 and 09/14	0.20	$S = -0.0000014F^2+ 65$
Logarithm	02/23/06	0.16	$S= -5.31Ln(F) + 101.22$
	09/14/07	0.22	$S= -7.13Ln(F) + 113.9$
	Combined data of 02/23 and 09/14	0.20	$S= -6.26Ln(F) + 107.9$
Expo	02/23/06	0.18	$S= 68.4e^{-0.00006F}$
	09/14/07	0.21	$S= 69.4e^{-0.00008F}$
	Combined data of 02/23 and 09/14	0.20	$S= 68.9e^{-0.00007F}$

4.1.3 Normal Conditions for I-495

Figure 4.3 shows that for I-495, the speed range is 15.35 mph with a minimum speed of 39.91 and a maximum speed of 55.26 mph. The flow rate range is between 760 and 1600 vphpl with a difference of 840 vphpl. The average speed on I-495 decreases faster than the speed on Route 46. Under normal conditions the data consist of both uncongested and congested parts on I-495. After removing the data for the congested part of the curve, the curve for the uncongested part remains and is used as the speed-flow relationship. Figure 4.3 shows the speed-flow relationship using a quadratic regression curve because the R^2 of the quadratic curve is greater than the R^2 of the linear, logarithmic, and exponential regression curves as shown in Table 4.11. Table 4.11 shows the R^2 and the coefficients of the linear, quadratic, logarithmic, and exponential regression curves.

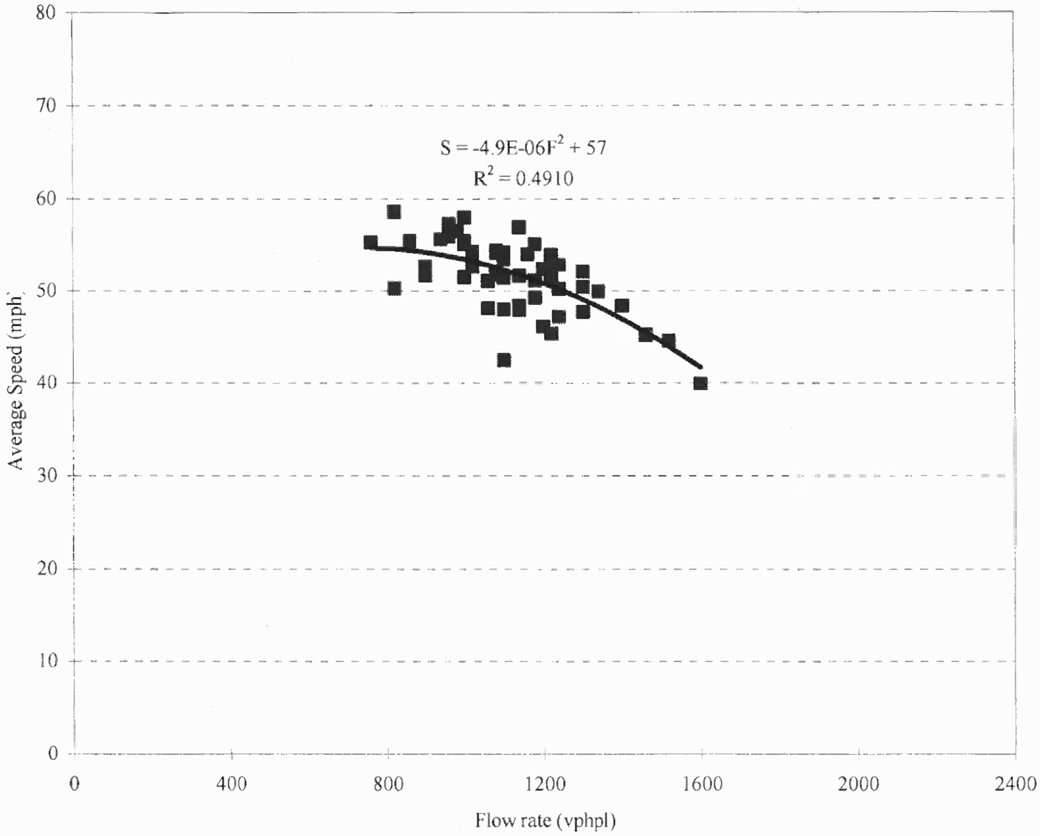

Figure 4.3 Speed-Flow Curves on I-495 under Normal Conditions

Table 4.11 Speed-Flow Regression Model for I-495 - Normal

Regression form	R^2	Regression Equations
Linear	0.42	S= -0.0145F+ 67.7
Quad	0.49	$S = -0.0000049F^2 + 57$
Logarithm	0.38	S= -15.59Ln(F) +160.8
Expo	0.42	$S= 71.2e^{-0.0003F}$

4.1.4 Normal Conditions for I-80

For I-80, the speed range is 19.56 mph with a minimum speed 52.79 and ae maximum speed 72.35 mph. The flow rate range is between 600 and 2220 vphpl with a difference of 1620 vphpl. The range of average speed on I-80 is greater than that on Route 46. Figure 4.4 shows the speed-flow relationships using a quadratic regression curve because the R^2 of the quadratic regression curve is greater than the R^2 of the linear, logarithmic, and exponential regression curves as shown in Table 4.12.

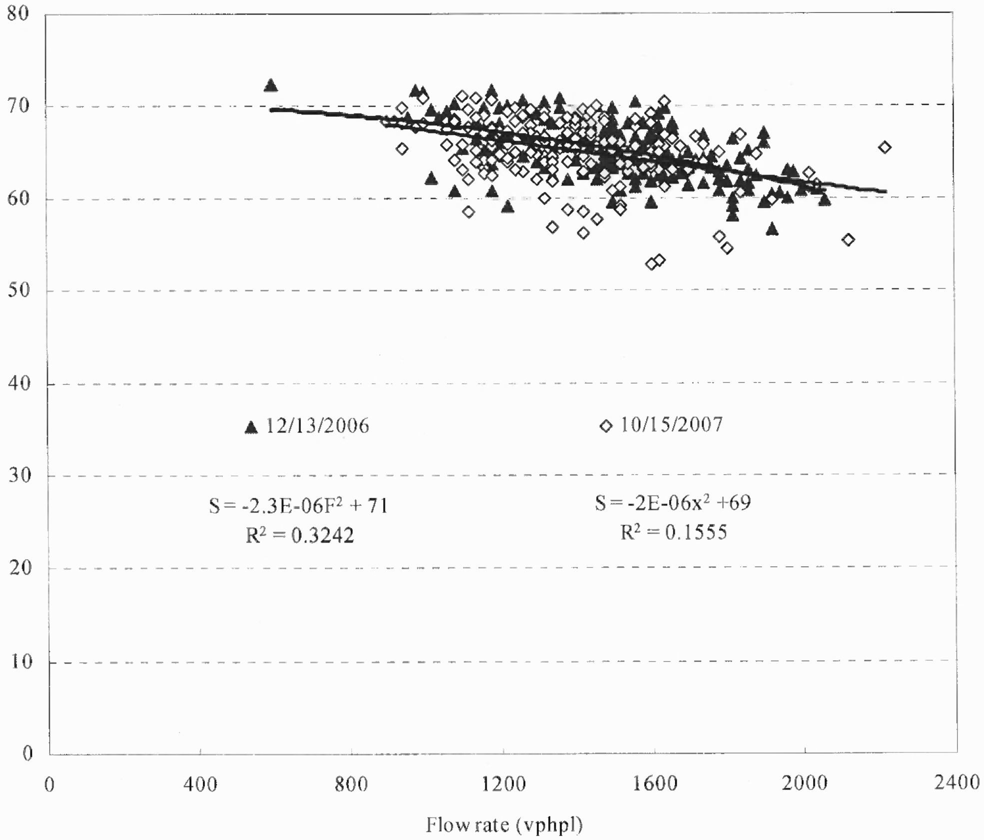

Figure 4.4 Speed-Flow Curves on I-80 under Normal Conditions

Table 4.12 shows the R^2 and the coefficients of the linear, quadratic, logarithmic, and exponential regression curves. The R^2 on Dec.13 is greater than the R^2 on Oct.15.

Table 4.12 Speed-Flow Regression Model for I-80 – Normal

Regression form	Date	R^2	Regression Equations
Linear	12/13/06	0.32	$S= -0.0068F+ 75.5$
	10/15/07	0.16	$S= -0.0059F+ 73.5$
	Combined data of 12/13 and 10/15	0.21	$S= -0.0061F+ 74.0$
Quad	12/13/06	0.32	$S = -0.0000023F^2+71$
	10/15/07	0.16	$S = -0.000002F^2+69$
	Combined data of 12/13 and 10/15	0.22	$S = -0.0000042F^2+76$
Logarithm	12/13/06	0.31	$S= -9.41Ln(F) + 133.87$
	10/15/07	0.16	$S= -8.40Ln(F) + 125.9$
	Combined data of 12/13 and 10/15	0.21	$S= -8.43Ln(F) + 126.4$
Expo	12/13/06	0.32	$S= 76.2e^{-0.0001F}$
	10/15/07	0.15	$S= 74.2e^{-0.00009F}$
	Combined data of 12/13 and 10/15	0.21	$S= 74.6e^{-0.00009F}$

4.1.5 Normal Conditions for Each Roadway

Figure 4.5 shows all of the curves presented in Figure 4.1 to 4.4. For Route 3 the average speed decreases slightly when the flow rate increases. The speed-flow curves show in Figure 4.5 are derived from two days of data except for I-495 whose curve is derived from one day of data.

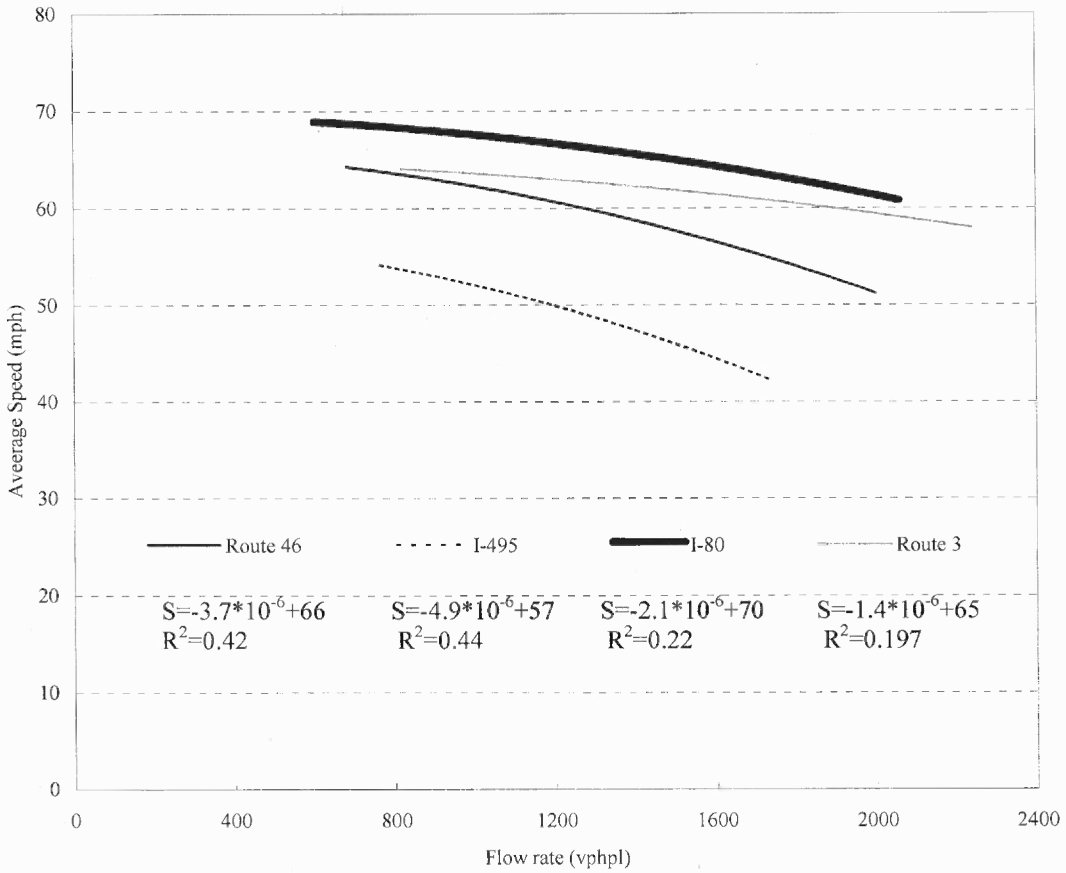

Figure 4.5 Speed-Flow Curves under Normal Conditions

4.2 Speed-Flow Models under Rain Conditions

Figures 4.6 to 4.9 show the speed-flow models for Route 46, Route 3, and I-80 under rain conditions. Under rain conditions, the speed-flow model for I-495 was not developed because the data was gathered under congested conditions.

4.2.1 Rain Conditions for Route 46

Fort Route 46, the speed range is 33.07 mph with a minimum speed of 36.48 and a maximum speed of 69.55 mph when the rain intensity is 0.03 inches/hr. The flow rate range is between 820 and 1840 vphpl with a difference of 1020 vphpl when the rain intensity is 0.03 inches/hr. The range of the average speed under rain conditions is greater than under normal conditions. The flow rate range under rain conditions is less than under normal conditions. Figure 4.6 shows the speed-flow relationship using a quadratic regression curve.

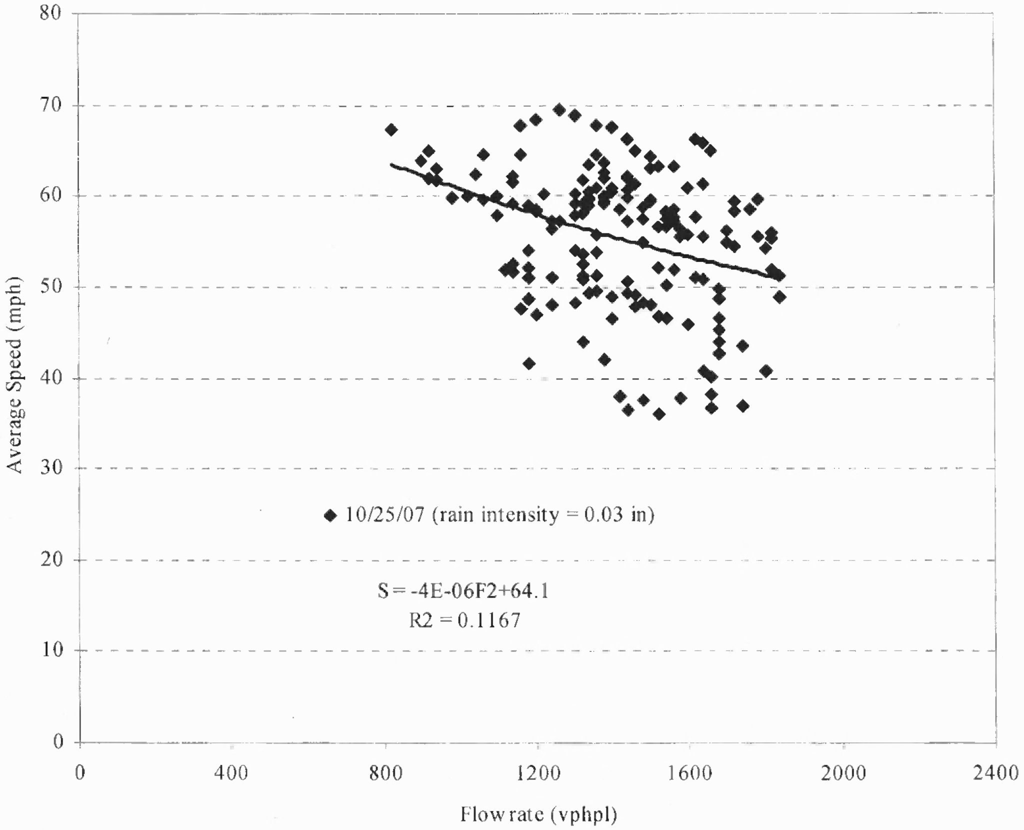

Figure 4.6 Speed-Flow Curves on Rte 46 under Rain Conditions

Table 4.13 shows the R^2 and the coefficients of the linear, quadratic, logarithmic, and exponential regression curve.

Table 4.13 Speed-Flow Regression Model for Rte 46 - Rain

Regression form	Date	R^2	Regression Equations
Linear	10/25/07	0.12	$S= -0.012F+ 72.3$
Quad	10/25/07	0.12	$S = -0.000004F^2+64$
Logarithm	10/25/07	0.12	$S= -16.1Ln(F) + 172.2$
Expo	10/25/07	0.11	$S= 75.33e^{-0.0002F}$

4.2.2 Rain Conditions for Route 3

Figure 4.7 shows the speed-flow relationships under rain conditions under different rain intensities, on Route 3. The speed range is 18.11 mph with a minimum speed of 40.18 and a maximum speed 58.29 mph when the rain intensity is 0.03 inches/hr. The speed range is 14.76 mph with a minimum speed of 34.68 and a maximum speed of 49.44 mph when the rain intensity is 0.22 inches/hr. The flow rate range is between 1060 and 2280 vphpl with a difference of 1220 vphpl when the rain intensity is 0.03 inches/hr. The flow rate range is between 1000 and 1920 vphpl with a difference of 920 vphpl when the rain intensity is 0.22 inches/hr. The range of average speed under rain conditions is greater than it is under normal conditions. The flow rate range under rain conditions is less than it is under normal conditions. The speed range when the rain intensity is 0.02 inches (< 0.1 inches) is greater than when the rain intensity is 0.20 inches (> 0.1 inches). Figure 4.7 shows the speed-flow relationships using a quadratic regression curve because the R^2 of the quadratic regression curve is greater than the R^2 of the linear, logarithmic, and exponential regression as shown in Table 4.14.

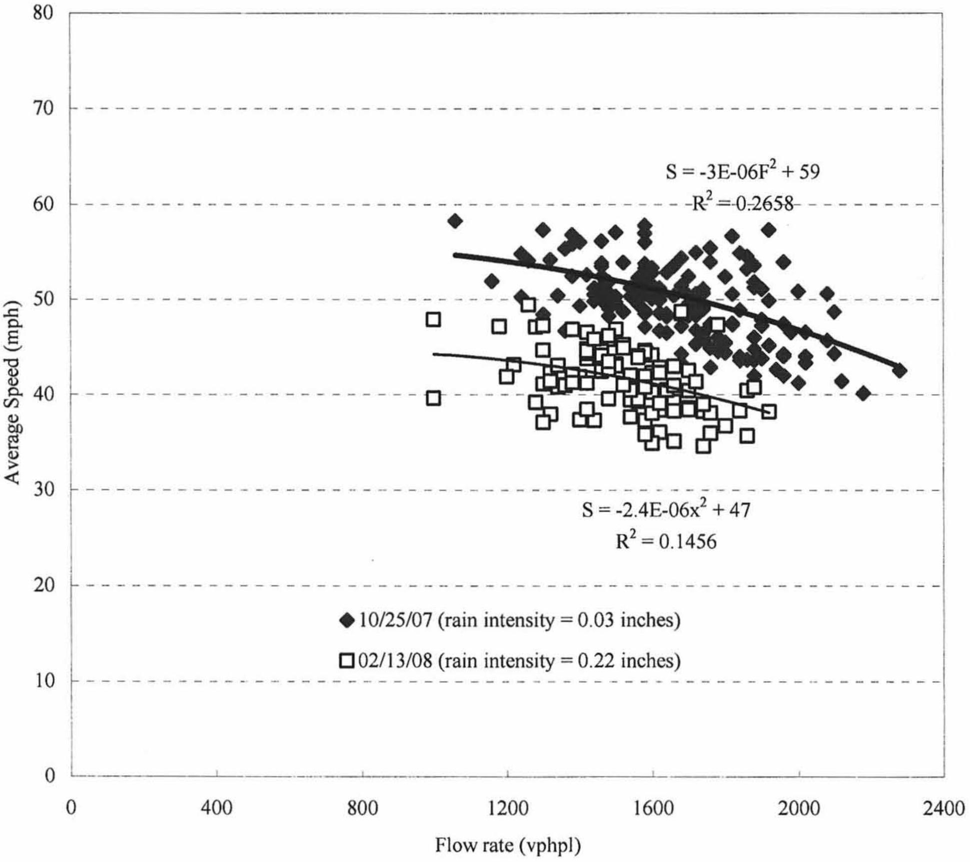

Figure 4.7 Speed-Flow Curves on Rte 3 under Rain Conditions

Table 4.14 shows the R^2 and the coefficients of the linear, quadratic, logarithmic, and exponential regression curve. The R^2 on Dec.25 is greater than the R^2 on Feb.13. The model is better fitting when rain intensities are smaller on Route 3.

Table 4.14 Speed-Flow Regression Model for Rte 3 - Rain

Regression form	Date	R^2	Regression Equations
Linear	10/25/07	0.26	$S= -0.01F+ 66.9$
	02/13/08	0.14	$S= -0.007F+ 52.4$
Quad	10/25/07	0.27	$S = -0.000003F^2+59$
	02/13/08	0.15	$S = -0.0000024F^2+47$
Logarithm	10/25/07	0.26	$S= -16.06Ln(F) + 169.3$
	02/13/08	0.14	$S= -10.2Ln(F) + 116.6$
Expo	10/25/07	0.27	$S= 70.33e^{-0.0002F}$
	02/13/08	0.14	$S= 53.9^{.0002F}$

4.2.3 Rain Conditions for I-80

Figure 4.8 shows results from the rain conditions of various rain intensities, on I-80. For I-80, the speed range is 22.46 mph with a minimum speed of 49.69 and a maximum speed of 72.15 mph when the rain intensity is 0.02 inches/hr and the speed range is 14.81 mph with a minimum speed 41.69 and a maximum speed of 56.50 mph when the rain intensity is 0.20 inches/hr. The flow rate range is between 920 and 2100 vphpl with a difference is 1180 vphpl when the rain intensity is 0.02 inches/hr and the flow rate range is between 880 and 1820 vphpl with a difference is 940 vphpl when the rain intensity is 0.20 inches/hr. The flow rate range under rain conditions is less than that under normal conditions. The speed range when rain intensity is 0.02 inches (< 0.1 inches) is greater than when the rain intensity is 0.20 inches (> 0.1 inches). Figure 4.8 shows the speed-flow relationships using a quadratic regression curve because the R^2 of the quadratic regression curve is greater than the R^2 of the linear, logarithmic, and exponential regression curves in Table 4.15. Table 4.15 shows the R^2 and the coefficients of the linear, quadratic, logarithmic, and exponential regression curves. The R^2 on Dec.25 and on Apr.14 are not much different. It indicates that the rain intensities do not affect the fit of the regression curve on I-80.

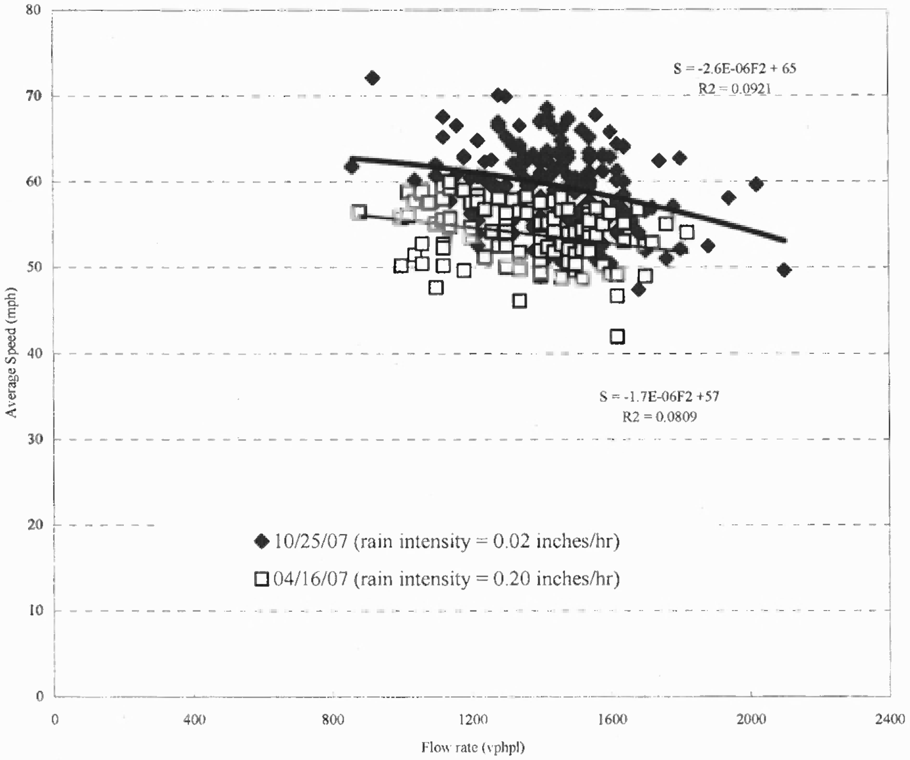

Figure 4.8 Speed-Flow Curves on I-80 under Rain Conditions

Table 4.15 Speed-Flow Regression Model for I-80 - Rain

Regression form	Date	R^2	Regression Equations
Linear	10/25/07	0.09	S= -0.0076F+ 70.4
	04/16/07	0.08	S= -0.0047F+ 60.3
Quad	10/25/07	0.09	$S = -0.0000026F^2+65$
	04/16/07	0.08	$S = -0.0000017F^2 +57$
Logarithm	10/25/07	0.08	$S= -10.53Ln(v_p) + 135.96$
	04/16/07	0.08	$S= -6.1218Ln(v_p) + 98.056$
Expo	10/25/07	0.09	$S= 71.46e^{-0.0001vp}$
	04/16/07	0.08	$S= 60.616e^{-0.00009vp}$

4.2.4 Rain Conditions for Each Roadway

Figures 4.9 and 4.10 combine the results of Figures 4.6 to 4.8. The speed-flow relationships for different locations are shown in Figure 4.9 when the rain intensity is less than 0.1 inches/hr and in Figure 4.10 when the rain intensity is greater than 0.1 inches/hr.

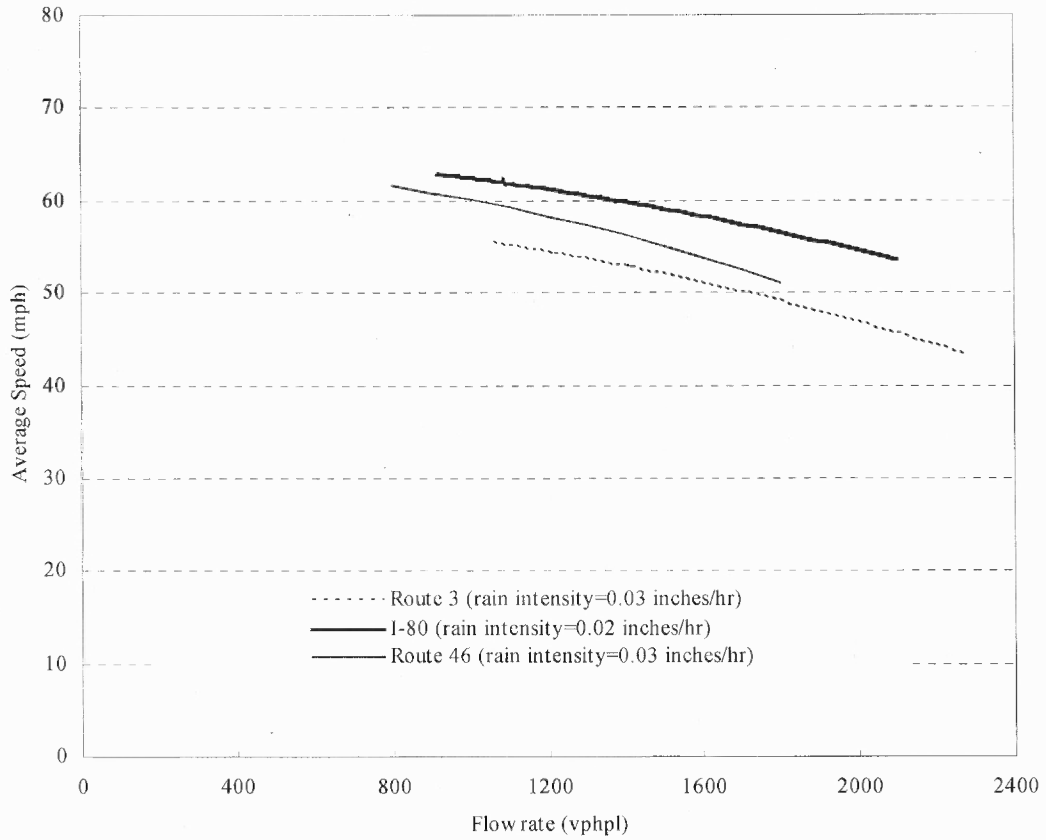

Figure 4.9 Speed-Flow Curves when Rain Intensity is Less Than 0.1 inches/hr

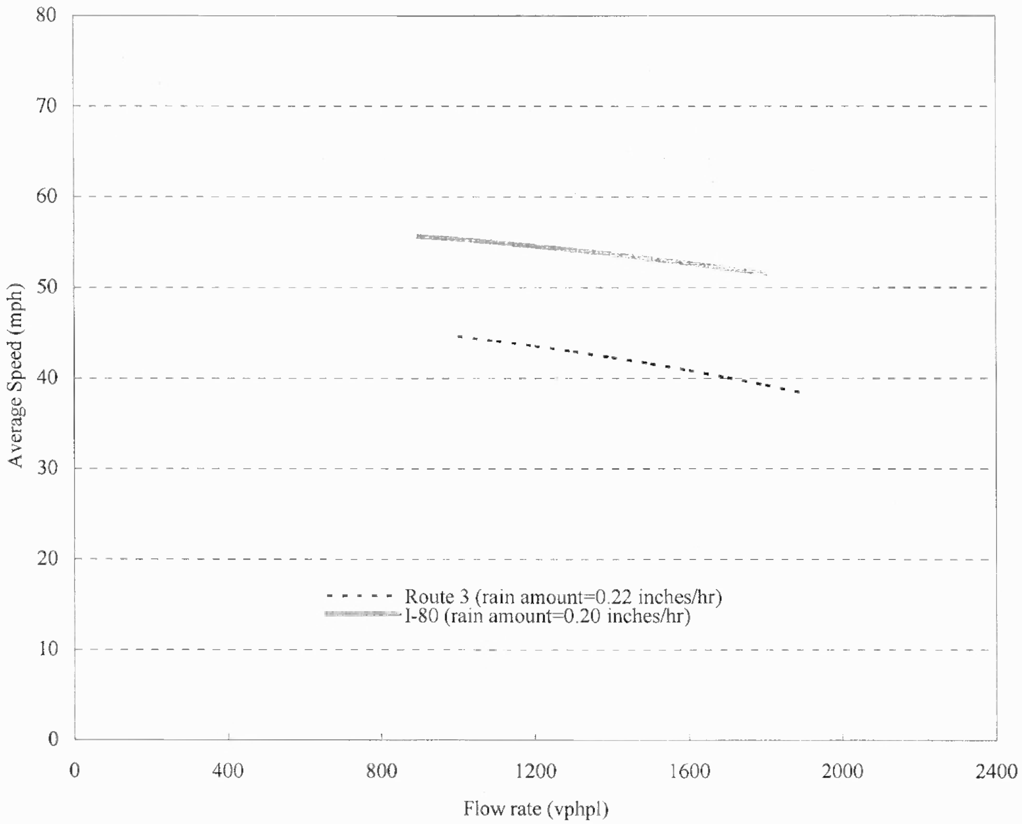

Figure 4.10 Speed-Flow Curves when Rain Intensity is Greater Than 0.1 inches/hr

4.3 Speed-Flow Models under Congested Conditions

Figures 4.11 to 4.13 show the Speed-flow models for I-495 and Route 46 under congested conditions. Models for congested conditions, the curves of Route 3 and I-80 cannot be shown because only data representing uncongested conditions exist.

4.3.1 Normal-Congested Conditions

For I-495, the speed range is 31.33 mph with a minimum speed of 8.58 and a maximum 39.91 mph. The flow rate range is between 520 and 2260 vphpl with a difference of 1740 vphpl. The flow rate range under normal-congested conditions is greater than that under normal conditions.

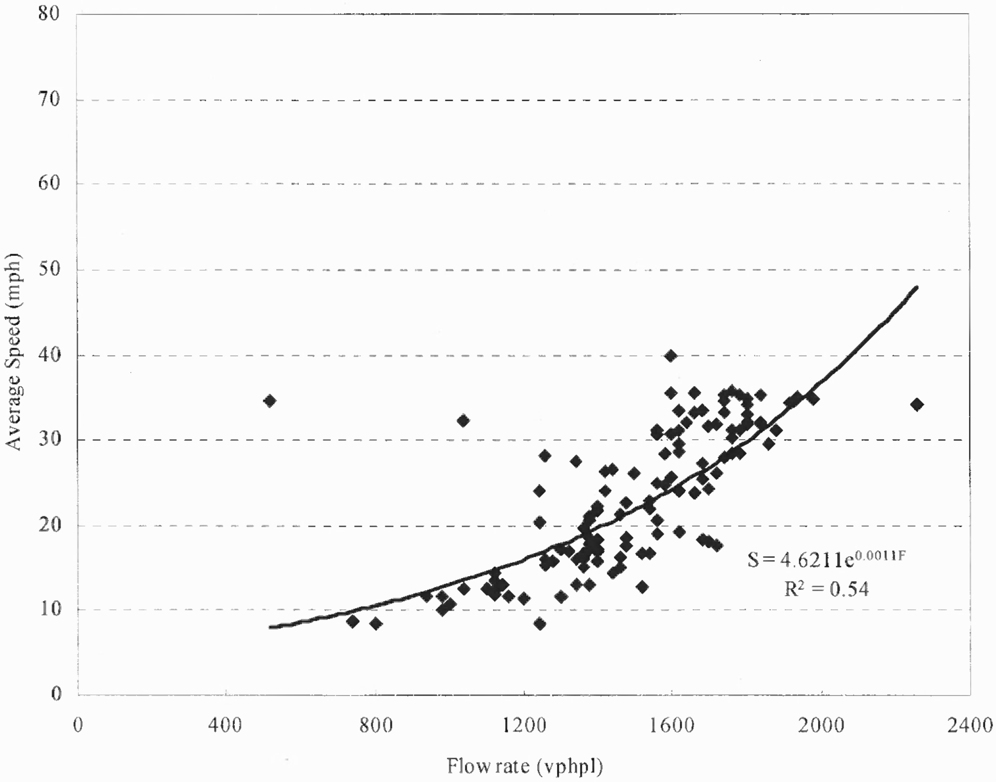

Figure 4.11 Speed-Flow Curves on I-495 under Normal-Congested Conditions

Figure 4.11 shows the speed-flow relationship using an exponential regression curve because the R^2 of the exponential regression curve is greater than the R^2 of the linear, quadratic, and logarithmic regression curves as shown in Table 4.16. Table 4.16 shows the R^2 and the coefficients of the linear, quadratic, logarithmic, and exponential regression curves.

Table 4.16 Speed-Flow Regression Model for Normal-Congested Conditions on I-495

Regression form	R^2	Regression Equations
Linear	0.49	$S= 0.02F-8.5$
Quad	0.54	$S = 0.000007F^2 +5$
Logarithm	0.39	$S= 24.9Ln(F) -158$
Expo	0.54	$S = 4.6e^{0.0011F}$

4.3.2 Rain-Congested Conditions

Figure 4.12 shows the speed-flow models on Route 46 under rain-congested conditions. For Route 46, the speed range is 27.41 mph with a minimum speed of 12.37 and a maximum speed of 39.78 mph when rain intensity is 0.11 inches/hr. The flow rate range is between 400 and 1740 vphpl with a difference of 1340 vphpl when rain intensity is 0.11 inches/hr. The flow rate range under rain-congested conditions is greater than that under rain conditions. Figure 4.12 shows speed-flow relationships using an exponential regression curve because the R^2 of the exponential regression curve is greater than the R^2 of the linear, quadratic, and logarithmic regression curves as shown in Table 4.17. Table 4.17 shows the R^2 and the coefficients of the linear, quadratic, logarithmic, and exponential regression curves.

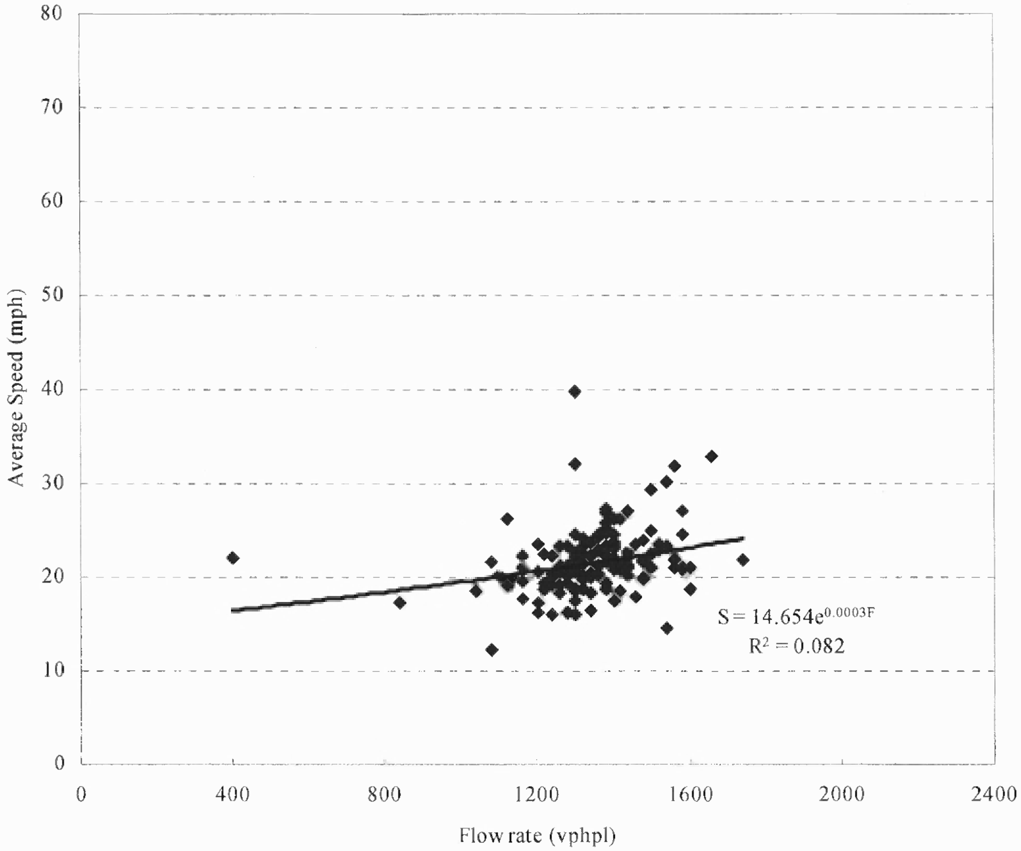

Figure 4.12 Speed-Flow Curves on Rte 46 when Rain Intensity is 0.11 inches/hr

Table 4.17 Speed-Flow Regression Model for Rain-Congested Conditions on Rte 46

Regression form	R^2	Regression Equations
Linear	0.07	S= 0.006F+13.4
Quad	0.08	$S = -0.0000027F^2 +16.8$
Logarithm	0.04	S= 5.5Ln(F) -17
Expo	0.08	$S = 14.6e^{0.0003F}$

Figure 4.13 shows the speed-flow models on I-495 under rain-congested conditions. For I-495, the speed range is 32.64 mph with a minimum speed of 4.12 and a maximum

speed 36.76 mph when the rain intensity is 0.21 inches/hr. The flow rate range is between 380 and 2040 vphpl with a difference of 1660 vphpl.

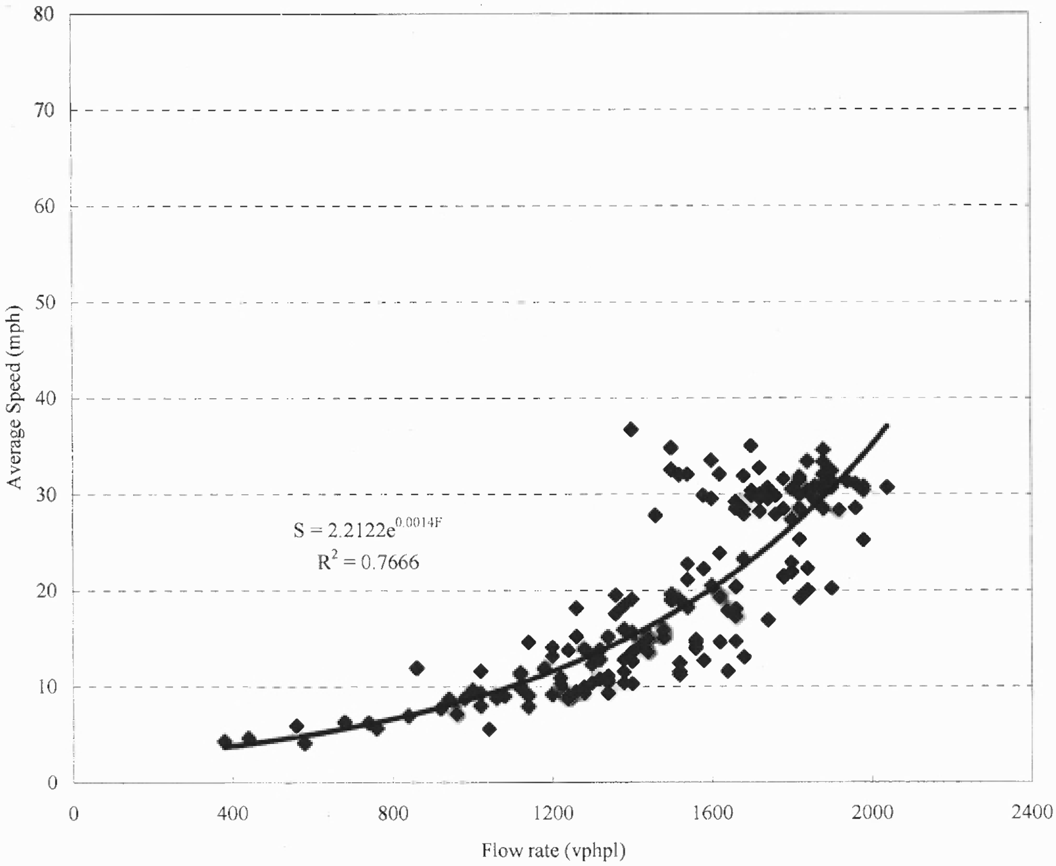

Figure 4.13 Speed-Flow Curves on I-495 when Rain Intensity is 0.21 inches/hr

Figure 4.13 shows the speed-flow relationship using an exponential regression curve because the R^2 of the exponential regression curve is greater than the R^2 of the linear, quadratic, and logarithmic regression curves as shown in Table 4.18. Table 4.18 shows the R^2 and the coefficients of the linear, quadratic, logarithmic, and exponential regression curves.

Table 4.18 Speed-Flow Regression Model for Rain-Congested Conditions on I-495

Regression form	R^2	Regression Equations
Linear	0.65	$S= 0.02F-13.2$
Quad	0.68	$S = -0.000006F^2 +0.5$
Logarithm	0.56	$S= 24.8Ln(F) -160.6$
Expo	0.76	$S = 2.2e^{0.0014F}$

4.3.3 Congested Conditions for Each Roadway

Figure 4.14 contains the combined results of Figures 4.11 to 4.13. The speed flow curves represent different locations and precipitation levels.

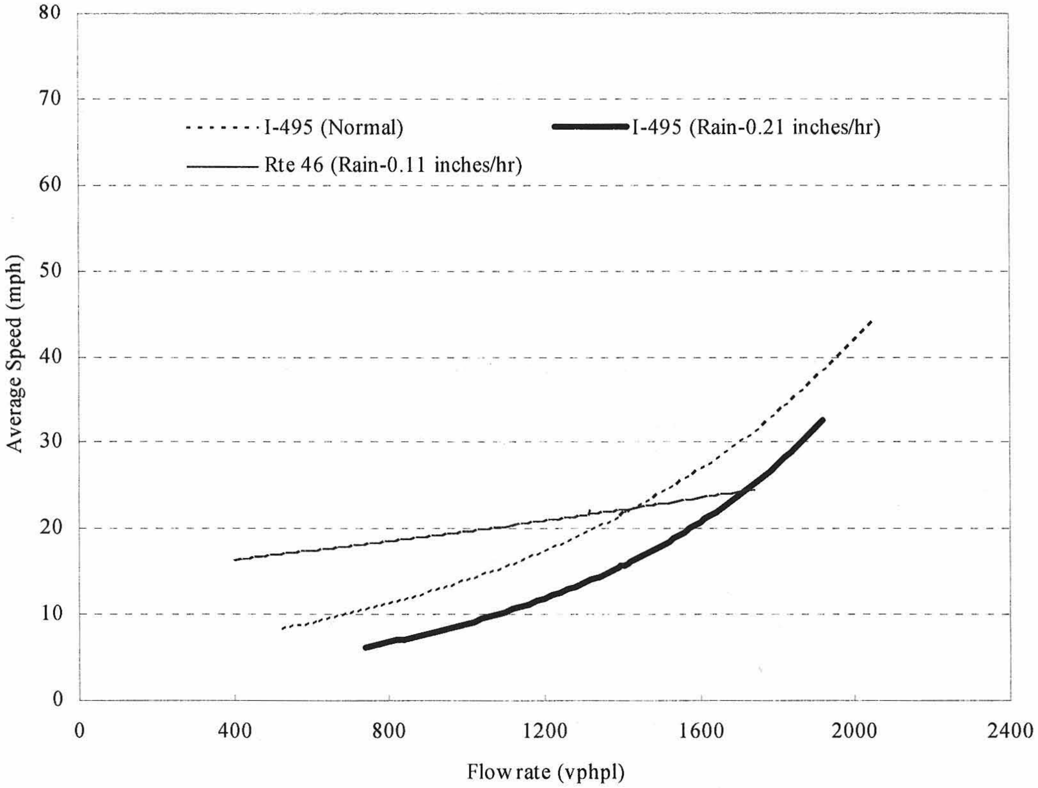

Figure 4.14 Speed-Flow Curves: Normal-Congested and Rain-Congested Conditions

Tables 4.19 and 4.20 show the combined results from Tables 4.9 to 4.18. The minimum speed decreases and the minimum flow rate increases from normal to rain conditions. Under congested conditions, the minimum speed and the minimum flow rate decreases from normal to rain conditions. The speed range increases and the flow rate range decreases from normal to rain conditions. Both speed range and flow rate do not change much from normal-congested to rain-congested conditions.

Tables 4.21 through 4.23 show the impact of rain and congestion for speed and flow rate ranges. Under rain conditions, the speed range increases of 9.75 mph at Route 46 with a rain intensity of 0.02 inches/hr and decreases by 4.75 mph at I-80 with a rain intensity of 0.20 inches/hr. The flow rate decrease between 680 vphpl at I-80 with a rain intensity of 0.20 inches/hr and 200 vphpl at Route 3 with a rain intensity of 0.03 inches/hr. The speed range increases under light rain intensity and decreases under moderate/heavy rain intensity.

Between normal-congested and rain-congested conditions, the speed range increases 4% at I-495 with a rain intensity of 0.21 inches/hr. The flow rate decreases 5% at I-495 with a rain intensity of 0.21 inches/hr. Between normal and normal-congested conditions, the speed range increases by 104% and the flow rate increases by 107% at I-495.

Table 4.19 Data and Regression Equations under Normal and Rain Conditions

	Weather	Date or Precipitation	Max and Min. Speed	Speed range	Max. and Min. Flow rate	Flow rate range	R^2 (%)	Regression equation
Rte 46	Normal	12/13/06	50.93-63.95	13.02	680-2000	1320	50.8	$S=-2.6*10^{-6}F^2+63$
	Normal	12/22/06	54.52-74.25	19.73	560-1660	1100	24.3	$S=-3.2*10^{-6}F^2+67$
	Normal	12/13+12/22	50.93-74.25	23.32	560-2000	1440	42.0	$S=-3.7*10^{-6}F^2+66$
	Rain	0.02 inches/hr	36.48-69.55	33.07	820-1840	1020	11.6	$S=-4*10^{-6}F^2+64$
Rte 3	Normal	02/23/07	54.10-71.02	16.92	820-2240	1420	18.9	$S=-1.2*10^{-6}F^2+65$
	Normal	09/14/07	54.70-68.37	13.67	1020-2020	1000	21.7	$S=-1.5*10^{-6}F^2+65$
	Normal	02/23+09/14	54.10-71.02	16.92	820-2240	1420	19.7	$S=-1.4*10^{-6}F^2+65$
	Rain	0.03 inches/hr	40.18-58.29	18.11	1060-2280	1220	26.6	$S=-3*10^{-6}F^2+59$
	Rain	0.22 inches/hr	34.68-49.44	14.76	1000-1920	920	14.6	$S=-2.4*10^{-6}F^2+47$
I-495	Normal	01/22/07	39.91-55.26	15.35	760-1600	840	44.1	$S=-6.4*10^{-6}F^2+60$
I-80	Normal	12/13/06	56.56-72.35	15.79	600-2060	1460	32.4	$S=-2.3*10^{-6}F^2+71$
	Normal	10/15/07	52.79-71.22	18.43	900-2220	1320	15.5	$S=-2.0*10^{-6}F^2+69$
	Normal	12/13+10/15	52.79-79.35	19.56	600-2220	1620	22.0	$S=-2.1*10^{-6}F^2+70$
	Rain	0.02 inches/hr	49.69-72.15	22.46	920-2100	1180	9.2	$S=-2.6*10^{-6}F^2+65$
	Rain	0.20 inches/hr	41.69-56.50	14.81	880-1820	940	8.1	$S=-1.7*10^{-6}F^2+57$

Table 4.20 Data and Regression Equations under Normal-Congested and Rain-Congested Conditions

	Weather	Date or Precipitation	Max and Min. Speed	Speed range	Max and Min. Flow rate	Flow rate range	R^2 (%)	Regression equation
I-495	Normal	01/22/07	8.58-39.91	31.33	520-2260	1740	54.0	$S=4.6*e^{0.0011*F}$
	Rain	0.21 inches/hr	4.12-36.76	32.64	380-2040	1660	76.7	$S=2.21*e^{0.0014*F}$
Rte 46	Rain	0.11 inches/hr	12.37-39.78	27.41	400-1740	1340	8.0	$S=14.6*e^{0.0003*F}$

Table 4.21 Rain Impact of Data Range between Normal and Rain Conditions

	Precipitation	Speed Range	Flow rate Range
Rte 46	0.02 inches/hr	9.75(42%)	-420(-29%)
Rte 3	0.03 inches/hr	1.19 (7%)	-200(-14%)
	0.22 inches/hr	-2.16(-13%)	-500(-35%)
I-80	0.02 inches/hr	2.90(15%)	-440(-27%)
	0.20 inches/hr	-4.75(-24%)	-680(-42%)

Table 4.22 Rain Impact of Data Range between Normal-Congetsed and Rain-Congested Conditions

	Precipitation	Speed Range	Flow rate Range
I-495	0.21 inches/hr	1.31(4%)	-80(-5%)

Table 4.23 Congestion Impact of Data Range between Normal and Normal-Congested Conditions

	Date	Speed Range	Flow rate Range
I-495	1/22/07	15.98(104%)	900(107%)

4.4 Proposed Speed-Flow Model

Using the data from the four study roadways, speed-flow models were developed under normal, rain and congested conditions. A nonlinear speed-flow model was investigated for its use with a quadratic, exponential and logarithmic functions used in developing the regression model.

This section describes the speed-flow relationships for the combined data from all roadways under normal, rain, and congested conditions. Two models are developed using the data for each roadway and the combined roadways under normal, rain, and congested conditions. First, the regression models are developed using each roadway (Route 46, Route 3, I-495, and I-80) under normal, rain, and congested conditions. Second, the regression model is developed using the combined roadways of Route 46, Route 3, and I-495, and I-80 under normal, rain, and congested conditions. These models are developed and then compared to each other. The model form is a quadratic function under normal conditions and an exponential function under congested conditions. As it was shown in the sections 4.1 through 4.3, for normal conditions the speed-flow model using a quadratic function has a slightly higher R^2 when compared to the exponential and logarithmic functions. For congested conditions, the exponential model showed the best fit under normal and rain conditions.

The variables used to develop the speed-flow model include precipitation, congestion, and flow rate as independent variables and speed as a dependent variable. The precipitation level is represented by a continuous regression variable, P. A dummy regression variable, C, is used to represent whether congested conditions exist where C is 0 when there is congestion and 1 otherwise. Density was used to identify when the roadway operated under congested conditions. The HCM 2000 states that the average density is 45 vpmpl under LOS F and LOS F can be considered as congested conditions. Table 4.24 shows the regression models and R^2 using data for each roadway and for the combined roadways.

Table 4.24 Speed-Flow Models Using Each Roadway and Combined Roadways

Data	Speed Flow Model	R^2 for Model
Rte 46 data	$S=63.5-43.8P-3.5*10^{-6}CF^2+(1-C)\left(-37.8+0.26e^{0.002F}+1.7Pe^{0.002F}\right)$	0.91
Rte 3 data	$S=67.6-73.3P-3.5*10^{-6}CF^2$	0.59
I-495 data	$S=51.7-37.4P+(1-C)\left(-33.5+0.47e^{0.002F}+0.8Pe^{0.002F}\right)$	0.88
I-80 data	$S=67.7-52.1P-1.7*10^{-6}CF^2$	0.46
Combined Roadways	$S=64.9-53.6P-2.3*10^{-6}CF^2+(1-C)\left(-43+0.4e^{0.002F}+1.2Pe^{0.002F}\right)$	0.86

Table 4.25 shows the t-test value, p value and VIF for each variable. Three values were used to produce the speed-intercept under congested conditions in Table 4.25. The values included the speed-intercept, the speed-intercept difference between normal and congested conditions, and the flow rate for congested conditions. For example, for the combined roadways the speed-intercept under congested conditions is calculated as $64.9-53.6*0-2.3*10^{-6}*0*0^2+(1-0)(-43+0.4e^{0.002*0}+1.2*0*e^{0.002*0})=64.9+(-43)+0.4e^{0.002*0}$ $=64.9+(-43)+0.4=22.3$ mph when C=0, P=0, and F=0.

Table 4.25 T-test, P-value, and VIF for Each Variable

Data	Variable (Coefficient)	T-test value	P-value	VIF
Rte 46 data	- Speed-intercept (63.5)	127.9	0.0	-
	- Precipitation (-43.8)	-6.4	$2.5*10^{-10}$	1.4
	- Flow rate ($-3.5*10^{-6}$)	-12.2	$3*10^{-31}$	2.7
	- Speed-intercept difference between normal and congestion* (-37.8)	-30.6	0.0	4.7
	- Flow rate for congestion (0.26)	13.8	$7*10^{-129}$	4.8
	- Interaction for flow and precipitation for congestion (1.7)	5.2	$2*10^{-7}$	4.7
Rte 3 data	- Speed-intercept (67.6)	99.1	0.0	-
	- Precipitation (-73.3)	-27.9	$1*10^{-111}$	1.0
	- Flow rate ($-3.5*10^{-6}$)	-13.6	$5*10^{-37}$	1.0
I-495 data	- Speed-intercept (51.7)	82.6	0.0	-
	- Precipitation (-37.4)	-6.6	$2 *10^{-88}$	4.8
	- Speed-intercept difference between normal and congestion (-33.5)	-36.6	$4*10^{-121}$	2.2
	- Flow rate for congestion (0.47)	15.2	$1*10^{-40}$	2.4
	- Interaction for flow and precipitation for congestion (0.8)	3.2	0.03	4.3
I-80 data	- Speed-intercept (67.7)	123.3	0.0	-
	- Precipitation (-52.1)	-23.4	$2.5*10^{-10}$	1.0
	- Flow rate ($-1.7*10^{-6}$)	-7.9	$3*10^{-31}$	1.0
Combined Roadways	- Speed-intercept (4.9)	169.9	0.0	-
	- Precipitation (-53.6)	-26.1	$2.5*10^{-10}$	1.5
	- Flow rate ($-2.3*10^{-6}$)	-12.6	$3*10^{-31}$	1.2
	- Speed-intercept difference between normal and congestion (-43)	-65.4	0.0	4.6
	- Flow rate for congestion (0.4)	14.2	$7*10^{-129}$	4.7
	- Interaction for flow and precipitation for congestion (1.2)	11.7	$2*10^{-7}$	2.1

* The coefficient of 'speed-intercept difference between normal and congestion' represents one of component of intercept under congested conditions.

Interpretation of speed-flow model using combined roadways

Considering the meaning of the regression coefficients in the multiple regression function, the 64.9 is the speed-intercept under normal conditions and 22.3 is the speed-intercept under normal-congested conditions using the combined roadway data. The speed-intercept indicates the speed when there is no precipitation and no volume on the roadway. Free-flow speed is the term used to describe the average speed that a motorist would travel if there were no congestion or other adverse conditions which indicates that the free-flow speed can be estimated only under normal conditions. HCM 2000 states the free-flow speed is 70 mph when the flow rate is less than 1300 pcphpl and 60 mph when flow rate is less than 1600 pcphpl. The free-flow speed and the ranges of flow rate, when the free-flow speed is defined, will be estimated in section 5.2.

For uncongested conditions the dummy variable representing the presence of congestion is C=1 and the model using the combined roadway data becomes $S = 64.9 - 53.6P - 2.3*10^{-6}F^2$. For congested conditions the dummy variable is C=0 and the model becomes $S=(64.9-43)-53.6P+0.4e^{0.002F}+1.2Pe^{0.002F}=21.9-53.6P+0.4e^{0.002F}+1.2Pe^{0.002F}$.

When precipitation is held constant at 0.1 inches/hr, the speed-flow model now becomes a relationship between speed and flow. The model is now shown as E{S} $=64.9-53.6(0.1)-2.3*10^{-6}F^2=59.54-2.3*10^{-6}F^2$. Note that this response function is a curve with slope, $-2.3*10^{-6}$. When the flow rate is held at 1000 vphpl, the speed-flow model now becomes the relationship between speed and precipitation. The function is now shown as E{S} $=64.9-53.6P-2*10^{-6}(10^6)=62.9-53.6P.$ The coefficient of the flow rate, which indicated the speed-flow relationship, is constant at $-2.3*10^{-6}$ when the precipitation level increases from 0 inches/hr to 0.1 inches/hr. The precipitation coefficient, which indicated the speed-precipitation relationship, is constant at -53.6 when the flow rate increases from 0 to 1000 vphpl. The speed-intercept decreases from 64.9 to 59.54 mph when the precipitation level increases from 0 to 0.1 inches/hr and there is no volume on the roadway (F=0). The speed-intercept decreases from 64.9 to 62.9 mph when the flow rate increases from 0 to 1000 vphpl and there is no rain on the roadway (P=0). The different speed-intercepts for speed-flow relationships have an additive effect on speed. The different speed-intercepts for speed-precipitation relationships have an additive effect on speed. It indicated same speed-flow and speed-precipitation relationship under normal and rain conditions.

Under congested conditions there is an interaction variable between flow rate and precipitation, such as$1.2Pe^{0.002F}$. Two variables of flow rate and precipitation effect on speed. Both the effect of flow rate for given level of precipitation and the effect of precipitation for given level of flow rate depend on the level of the other predictor variable. Suppose precipitation is 0.1 inches/hr. The speed-flow model is now shown as $E\{S\}$ $=21.9-53.6(0.1)+\underline{0.4e^{0.002F}}+1.2(0.1)e^{0.002F}=16.54+\underline{0.52e^{0.002F}}$. When the flow rate is1000 vphpl, the regression function is now shown as $E\{S\}$ $=21.9-\underline{53.6P}+0.4e^{0.002(1000)}+1.2Pe^{0.002(1000)}=(21.9+2.96)+(-53.6P+8.87P)=24.86\underline{-44.73P}.$ Under congested conditions the flow rate coefficient, which indicated speed-flow relationship, increases from 0.4 to 0.52 when precipitation increases from 0 to 0.1 inches/hr. The precipitation coefficient, which indicated speed-precipitation relationships, increases from -53.6 to -44.73 when the flow rate increases from 0 to 1000 vphpl. The speed-intercept decreases from 21.9 to 16.54 mph when precipitation increases from 0 to 0.1 inches/hr and there are no volume on the roadway, F=0. The speed-intercept increases from 22.3 to 24.86 mph when the flow rate increases from 0 to 1000 vphpl and no rain on the roadway, P=0. The different speed-intercepts for speed-flow relationship have an additive effect on speed. The different speed-intercepts for speed-precipitation relationship have an additive effect for speed. The different coefficients of flow rate and coefficients of precipitation have an interaction for speed-flow or speed-precipitation relationship which indicated there are different speed-flow and speed-precipitation relationships under congested conditions.

Overall, the speed-flow models show slight differences among the roadways. Speed-flow models for I-80 and Route 3 were not developed under congested conditions because the data were gathered under uncongested conditions. The speed-intercept for each roadway is similar with the free-flow speed observed data. The free-flow speed for the observed data on Route 46 and I-495 is less than that of Route 3 and I-80. Route 46 intersects with Route 3 East bound and there is an entrance ramp in the study location which may add considerable traffic. I-495 provides access to the Lincoln Tunnel, a major tunnel providing access to Manhattan, and has relatively high vehicular volumes causing heavy traffic congestion in the AM peak period.

The coefficient of the precipitation is negative indicating that results in a decrease in speed. Route 3 has the largest precipitation coefficient indicating speed has the largest reduction when there is precipitation on the roadway. Route 3 intersects with Route 1 and I-495. Under rain conditions congestion on I-495 may cause the speed decrease on Route 3.

The coefficients of the flow rate are all very low. The speed-flow models indicate that speed is not very sensitive to small increases in flow on any of the roadways. The flow rate coefficient on I-80 is lower than on other roadways. Route 46 and I-495 consist of three lanes in each direction and Route 3 consists of 4 lanes in each direction, and I-80 consists of two lanes for cars and three lanes for cars/trucks in each direction.

The models show good fit for Route 46, I-495, and the combined roadway data with an R^2 of 0.91, 0.88, and 0.86 respectively. On Route 3 and I-80, the R^2 are lower. The p-values are reported for the intercept and coefficient values in each of the speed-flow models developed. Figure 4.15 shows the speed-flow models under normal and normal-congested conditions which were presented in Table 4.24. There are slight differences among the models for Route 46, Route 3, I-495 and the combined data. Figure 4.16 shows the speed-flow models when the rain intensity is 0.1 inches/hr. The figure shows that there are different speed-intercepts for normal and rain conditions.

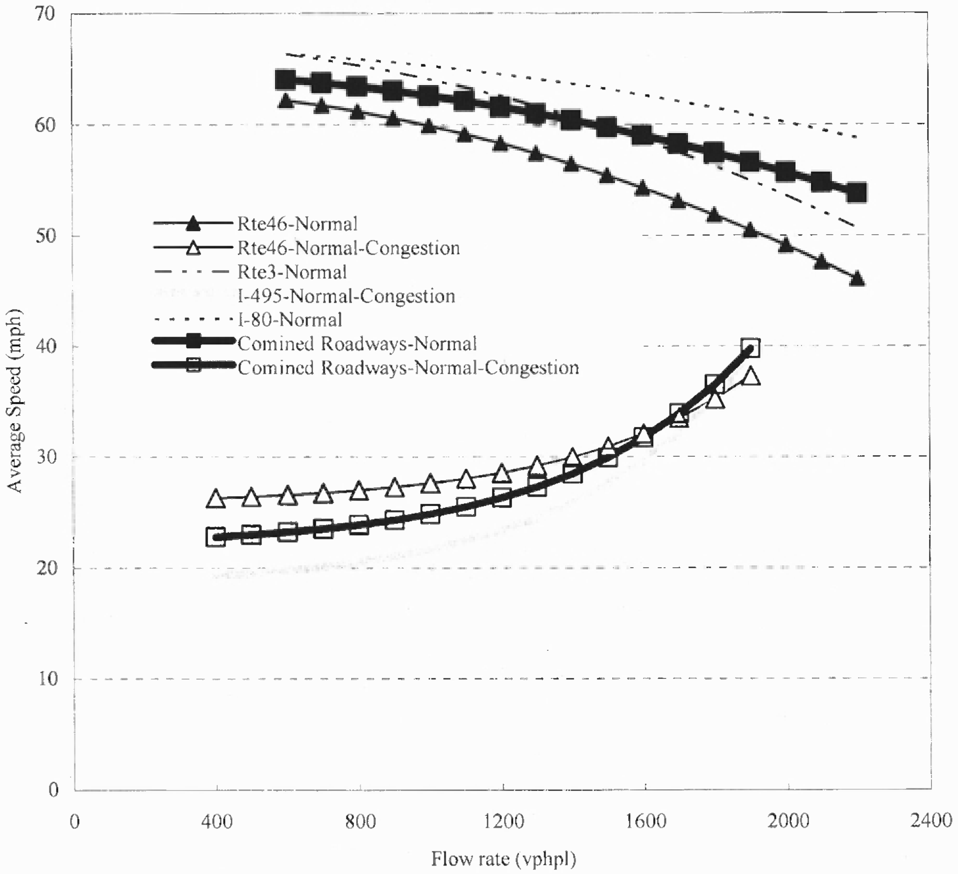

Figure 4.15 Speed-Flow Curves under Normal and Normal-Congested Conditions

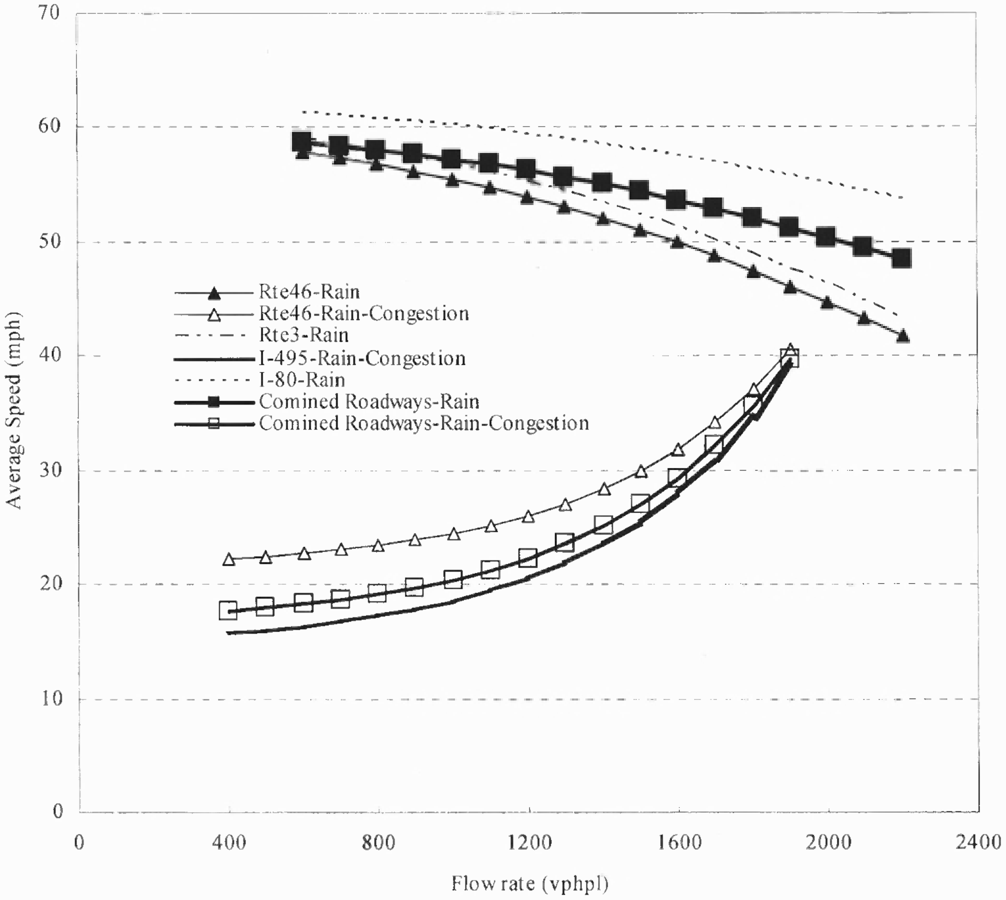

Figure 4.16 Speed-Flow Curves under Rain and Rain-Congested Conditions

To test whether there are statistically significant for speed differences using speed-flow regression equation models between the combined roadways and each roadway, the statistic test is used by Chi-square (χ^2) Test which is called as the tests of goodness of fit. It tests a null hypothesis that the frequency distribution of each roadway is consistent with the combined roadway data. The first step in the chi-square test is to calculate the chi-square statistic. The chi-square statistic is calculated by finding the difference between each roadway and the combined roadways, squaring them, dividing each by the combined roadways, and taking the sum of the results. The chi-square statistic can then be used to calculate a p-value and compare the value of the statistic to a chi-square distribution.

To test whether there is equality of the regression equation for the combined data and the regression equation for each roadway, i.e., to choose between the alternatives:

Hypothesis 1: H_0: $\text{Speed}_{\text{combined roadway}}=\text{Speed}_{\text{Rte46}}$ H_a: $\text{Speed}_{\text{combined roadway}} \neq \text{Speed}_{\text{Rte46}}$

Hypothesis 2: H_0: $\text{Speed}_{\text{combined roadway}}=\text{Speed}_{\text{Rte 3}}$ H_a: $\text{Speed}_{\text{combined roadway}} \neq \text{Speed}_{\text{Rte3}}$

Hypothesis 3: H_0: $\text{Speed}_{\text{combined roadway}}=\text{Speed}_{\text{I-80}}$ H_a: $\text{Speed}_{\text{combined roadway}} \neq \text{Speed}_{\text{I-80}}$

Hypothesis 4: H_0: $\text{Speed}_{\text{combined roadway}}=\text{Speed}_{\text{I-495}}$ H_a: $\text{Speed}_{\text{combined roadway}} \neq \text{Speed}_{\text{I-495}}$

Tables 4.26 and 4.27 summarized the Chi-square (χ^2) test under normal, rain, normal-congested, and rain-congested conditions. Table 4.26 shows that the p-values are greater than 0.05 under normal and rain conditions. It indicates that the speed-flow models between each roadway and the combined roadways are same.

Table 4.27 shows the p-values are greater than 0.05 on Route 46 and I-495 under normal-congested and rain-congested conditions. It indicates that there are same speed-flow models between each roadway and the combined roadways. The p-value is less than 0.05 on Route 46, which is 0.001, under rain-congested conditions when the flow rate ranges from 400 to 2000 vphpl.

Table 4.26 Chi-Square (χ^2) Test: Normal and Rain Conditions

	Normal Conditions			Rain Conditions		
	Rte 46[a]	**Rte 3**[a]	**I-80**[a]	**Rte 46**[a]	**Rte 3**[a]	**I-80**[a]
p-value	0.991	1.0	0.995	0.998	1.0	0.987

a: Flow ranges from 600 to 2200 vphpl

Table 4.27 Chi-Square (χ^2) Test: Normal-Congested and Rain-Congested Conditions

	Normal-Congested Conditions		Rain-Congested Conditions	
	Rte 46[a]	**I-495**[a]	**Rte 46**[b]	**I-495**[a]
p-value	0.998	0.992	0.069	1.0

a: Flow ranges from 400 to 2000 vphpl

b: Flow ranges from 800 to 2000 vphpl

The results of Tables 4.26 and 4.27 indicate that the regression model using the combined roadways can be used for all freeways in New Jersey. Based on the data and the results of Tables 4.26 and 4.27, the model has s better fit when the speed is less than about 70 mph, the rain intensity ranges from 0.01 and 0.24 inches/hr, there are three or four lanes in each direction and speed ranges from 50 to 55 mph. Figure 4.17 shows speed-flow curves for all roadways using the combined roadways data.

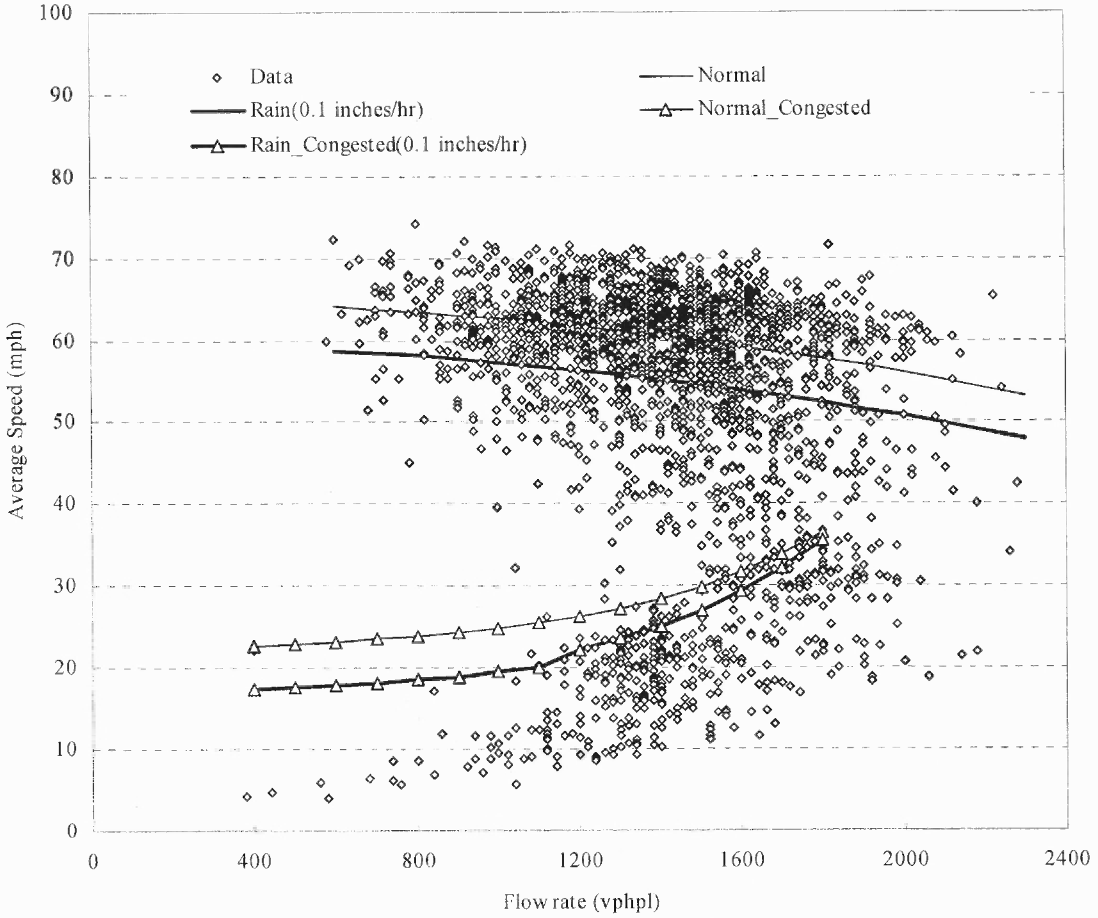

Figure 4.17 Speed-Flow Curves Using the Combined Roadways

CHAPTER 5

MODEL VALIDATION

5.1 Method of Checking Validity

Model validity refers to the stability and reasonableness of the regression coefficients, the plausibility and usability of the regression function, and the ability to generalize inferences drawn from the regression analysis. There are methods to examine the validity of the regression model against validation data. When the data set is large enough, it can be split the data into two sets: a model-building data set and a validation data set. The model building data set is the same as the combined roadway data in section 4.4. It is important, however, that the model-building data be sufficiently large so that a reliable model can be developed. The first set, called the model-building set, is used to develop the speed-flow model. The second data set, called the validation or prediction set, is used to evaluate the reasonableness and predictive ability of the selected model. In this research, the data for I-78 and Route 22 are used for the validation data set. The model building data set or the combined roadway data used data for Route 46, Route 3, I-495 and I-80.

The validation of the regression model involves also the appropriateness of variables selected, the magnitude of the regression coefficients, and the predictive ability of the model. Another approach for performing a validation is to re-estimate the model form chosen when building the model using the validation data.

A means of measuring the actual predictive capability of the selected regression model is to use this model to predict each case in the validation data set and then to calculate the mean of the squared prediction errors, to be denoted by MSPR. The MSPR can be calculated using Equation 5.1.

$$MSPR = \frac{\sum_{i=1}^{n*}(Y_i - \hat{Y}_i)^2}{n*} \tag{5.1}$$

where: Y_i is the value of respond variable in the ith validation data set

$\hat{Y}_i$ is the predicted value for the ith validation data set based on the regression model using model building data

n* is the number of cases in the validation data set

If the ratio of MSRP and MSE is more than the critical value determined by the F-distribution F(0.05, n, n*), the model is determined to be "suspect." The n is the number of cases in the data set for the speed-flow model and n* is the number of cases in the validation data set. The MSE is defined as shown in Equation 5.2.

$$MSE = \frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{n-k} \tag{5.2}$$

where: Y_i is the value of respond variable in the ith data set

$\hat{Y}_i$ is the predicted value for the ith data set based on the regression model

n is the number of cases in the data set

k is degrees of freedom

To validate the selected regression model, the data for I-78 and Route 22 had been held out for a validation data set. Equations 5.3 and 5.4 show the regression equations using the data of I-78 and Route 22. The models contain all significant variables for all weather conditions. The speed flow model for I-78 was not developed under congested conditions because the data were gathered under uncongested conditions. The speed-flow model for Route 22 was developed under all weather and congested conditions. Table 5.1 shows that the MSE value for the regression model using the model building data or the combined roadway data is 36.55.

$$S = 72.4 - 2.9 * 10^{-7} F^2 - 40.7P \qquad \text{for I-78} \tag{5.3}$$

$$S = 54.6 - 41.8P - 2.2 * 10^{-6} F^2 + (1 - C)(-24 + 0.013e^{0.002F}) \quad \text{for Route 22} \tag{5.4}$$

For the validation of I-78, the MSE and the MSPR are 20.4 and 37.18, respectively. If the ratio of the MSRP and the MSE is more than the critical value of 1.16, then the model is determined to be "suspect." The ratio is determined to be 1.02, indicating that the MSPR does not differ greatly from the MSE for model building data. It is reasonably valid indicator of the regression model's predictive ability.

Table 5.1 Models Using Model-Building and Validation Data

	Model using model building data	Model using validation data for I-78	Model using model building data	Model using validation data for Rte 22
MSE	36.55	20.4	36.55	49.8
MSPR	37.18	-	61.97	-

For the validation of Route 22, the MSE and the MSPR are 49.8 and 61.97, respectively. If the ratio of the MSRP and the MSE is 1.71 and more than the critical value of 1.19, then the model was determined to be "suspect."

For the model validation of I-78, under normal conditions the coefficient of flow rate, which is $-2.3*10^{-6}$, using model building data or the combined roadway data is greater than the validation data set of I-78 which is $-2.9*10^{-6}$. The coefficient is not significant as the p value is 0.366. The model using model building data or the combined roadway data is limited to speed levels of less than about 70 mph. The speeds data using I-78 ranges up to 85 mph and the speed limit is 65 mph.

For the model validation of Route 22, under normal conditions the coefficients of the flow rate, which are $-2.2*10^{-6}$ for Route 22 and $-2.3*10^{-6}$ for model building data, are similar. Under congested conditions the coefficients of flow rate, which are 0.013 for Route 22 and 0.4 for the model building data, are different coefficients. The VIF value for the coefficient of the flow rate, is 5.1 which is not significant for the speed-flow model using the data of Route 22. There are 2 lanes in each direction on Rte 22 but 3-4 lanes in each direction in the model building data and the speed limit is 40 mph on Route 22.

5.2 Validity of Flow rate Range Using Stratified (Cluster) Sampling

Stratification is valuable for improving the precision of data, by dividing the population of interest into strata homogeneous with respect to population attributes correlated with the variables of research interest (i.e., speed or flow rate). When sub-populations vary considerably, it is advantageous to sample each subpopulation (stratum) independently. Stratification is the process of grouping members of the population into relatively homogeneous subgroups before sampling. Figure 5. 1 shows the scatter-plot between speed and flow rate using the data for Route 46, Route 3, I-495 and I-80.

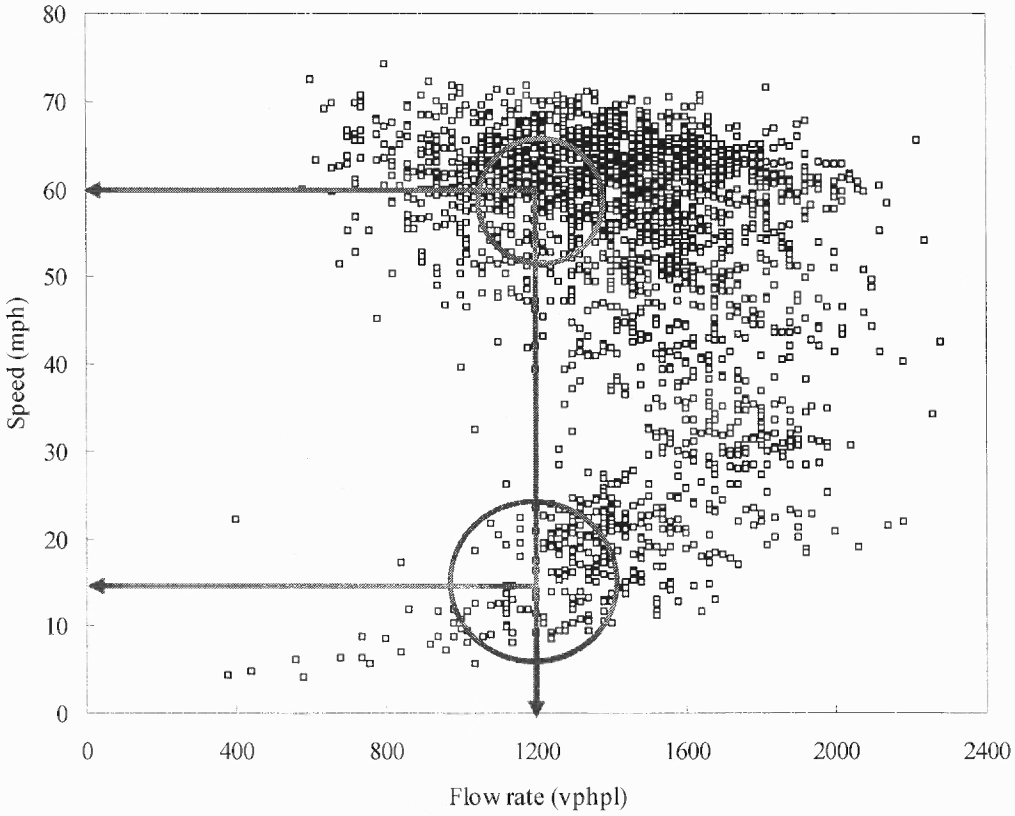

Figure 5.1 Scatter-plot of Speed and Flow

The sub-populations of flow rate are used because the strata should be mutually exclusive. If the sub-population of speed is used, there are two kinds of data of speed (i.e., one group of data is between 50 and 70 mph, and the other is between 10 and 30 mph) when the flow rate is 1200 vphpl. It is not mutually exclusive. The stratified (cluster) sampling analysis performed in this research is stated as follows.

- The flow rate is stratified from 0 to 400, 400 to 800, 800 to 1200, 1200 to 1600, 1600 to 2000, and 2000 to 2400 vphpl; and
- Compare the speed-flow model and speed-flow curve in HCM 2000

Figure 5.2 shows speed-flow regression curves for each strata sampling. Table 5.2 shows the speed-flow regression equations using 5 stratified samplings.

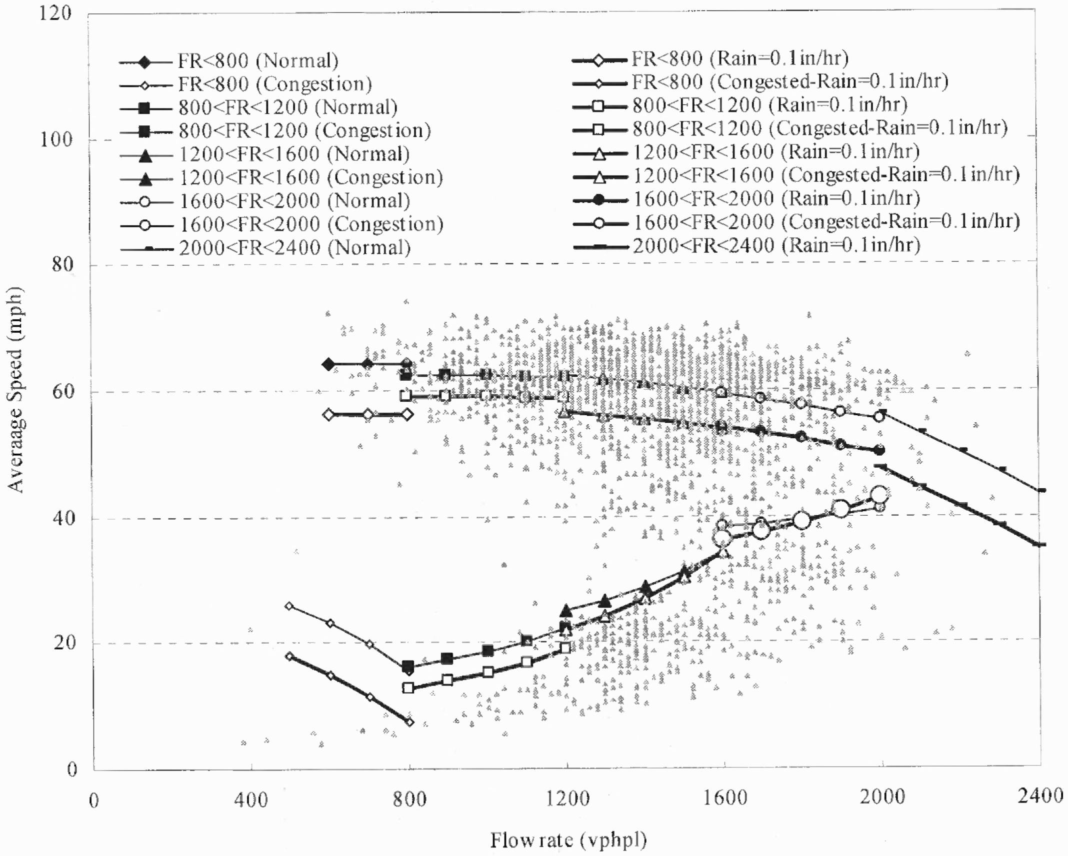

Figure 5.2 Speed-Flow Curves - 5 Stratified Samplings

Table 5.2 Speed-Flow Model Using 5 Stratified Samplings

Flow rate	Speed-Flow Model	R^2 for Model
$F<800$	$S = 64.4 - 82.1P - 2.3 \times 10^{-7} CF^2 + (1-C)\left(-26 + 4.7e^{0.002F}\right)$	0.58
$800 \leq F < 1200$	$S = 62.3 - 34.4P - 5.5 \times 10^{-7} CF^2 + (1-C)\left(-51.7 + 1.0e^{0.002F}\right)$	0.86
$1200 \leq F < 1600$	$S = 66.0 - 57.9P - 2.5 \times 10^{-6} CF^2 + (1-C)\left(-48.7 + (0.7 + 1.3P)e^{0.002F}\right)$	0.17
$1600 \leq F < 2000$	$S = 66.8 - 52.8P - 2.9 \times 10^{-6} CF^2 + (1-C)\left(-31.3 + (0.1 + 0.3P)e^{0.002F}\right)$	0.02
$2000 \leq F < 2400$	$S = 85.8 - 85.7P - 7.2 \times 10^{-6} CF^2$	0.57

Table 5.3 shows the t-test value, p-value, and VIF for each variable. Under normal conditions the p-values the flow rate coefficient, when the flow rate is less than 1200 vphpl and greater than 2000 vphpl, are greater than 0.05, which indicates that there are no strong relationships between speed and flow rate. Under congested conditions, the p-value for the flow rate coefficient, when the flow rate is less than 800 vphpl, is greater than 0.05, which indicates that there is no strong relationship between speed and flow rate. HCM 2000 states that the speed decreases when the flow rate is greater than 1300 pcphpl at FFS=70 mph when flow rate is greater than 1600 pcphpl at FFS=60 mph. The speed-flow model can be expressed when the flow rate ranges from 1200 vphpl to 2000 vphpl under normal condition. This methodology can give a statistically significant range of flows which fits the speed-flow regression model using the combined roadways. But the model in Table 5.2 cannot be used for all freeways in New Jersey because the value of VIF is greater than 5 for the flow rate coefficient under congested conditions.

Using the combined roadway, the speed-intercept is 61.59 mph when the flow rate is 1200 vphpl under normal conditions, and this is the estimate of the free-flow speed when flow rate ranges from 0 to 1200 vphpl. The p value of the flow rate coefficient is not significant when the flow rate is less than 1200 vphpl and greater than 2000 vphpl.

Table 5.3 T-test, P-value, and VIF for Each Variable Using 5 Stratified Samplings

Flow rate	Variable (Coefficient)	T-test value	P-value	VIF
F<800	- Speed-intercept (64.4)	10.5	$4*10^{-14}$	-
	- Precipitation (-82.1)	-4.2	0.001	3.0
	- Flow rate ($-2.3*10^{-7}$)	-0.02	0.98	2.9
	- Speed-intercept difference between normal and congestion (-26)	-2.2	0.03	34.8
	- Flow rate for congestion (4.7)	-1.7	0.09	25.5
800$\leq$F<1200	- Speed-intercept (62.3)	43.6	$5*10^{-169}$	-
	- Precipitation (-34.4)	-8.5	$2*10^{-16}$	1.3
	- Flow rate ($-5.5*10^{-7}$)	-0.45	0.65	1.1
	- Speed-intercept difference between normal and congestion (-51.7)	-11.6	$1*10^{-27}$	32.6
	- Flow rate for congestion (1.0)	2.1	0.04	32.2
1200$\leq$F<1600	- Speed-intercept (66.0)	53.6	0.0	-
	- Precipitation (-57.9)	-22.9	$3*10^{-96}$	1.6
	- Flow rate ($-2.5*10^{-6}$)	-4.1	$4*10^{-5}$	1.3
	- Speed-intercept difference between normal and congestion (-48.7)	-26.4	$3*10^{-121}$	22.1
	- Flow rate for congestion (0.7)	6.3	$4*10^{-10}$	22.9
	- Interaction for flow and precipitation for congestion (1.3)	8.7	$8*10^{-18}$	2.8
1600$\leq$F<2000	- Speed-intercept (66.8)	24.9	$2*10^{-92}$	-
	- Precipitation (-52.8)	-9.7	$2*10^{-20}$	2.1
	- Flow rate ($-2.9*10^{-6}$)	-3.4	0.0006	1.3
	- Speed-intercept difference between normal and congestion (-31.3)	-10.6	$5*10^{-24}$	24.1
	- Flow rate for congestion (0.1)	1.2	0.04	24.4
	- Interaction for flow and precipitation for congestion (0.3)	5.9	$5*10^{-9}$	2.5
2000$\leq$F<2400	- Speed-intercept (85.8)	3.7	0.001	-
	- Precipitation (-85.7)	-1.2	0.23	1.2
	- Flow rate ($-7.2*10^{-6}$)	-1.0	0.169	1.1

Under congested conditions the speed-flow model can be valid for flow rate range between 800 vphpl and 2000 vphpl. The p value of the flow rate coefficient is not significant when the flow rate is less than 800 vphpl. The interaction terms between flow and precipitation are as $1.3Pe^{0.002F}$ when flow rates are between 1200 and 1600 vphpl and $0.3Pe^{0.002F}$ when flow rates are between 1600 and 2000 vphpl. This indicates there are no different speed-flow relationships between normal-congested and rain-congested conditions when the flow rate is less than 1200 vphpl.

CHAPTER 6

DEVELOPMENT OF A RAIN ADJUSTMENT FACTOR

6.1 Introduction

In this chapter a methodology is proposed for use in the HCM to estimate the average speed under rain conditions using the speed data collected in this research. The procedure uses a rain adjustment factor, f_{Rain}, for a given precipitation and flow level to modify the existing procedures outlined in the HCM to estimate free-flow speed at basic freeway segments. The results of this research can be implemented within the basic freeway procedure of the Highway Capacity Manual (HCM) and can be used to improve the speed-flow relationships and the free-flow speed estimates provided in the Highway Capacity Manual (HCM 2000).

6.2 Estimating the Average Speed under Rain Conditions

HCM 2000 states that the free-flow speed is the mean speed of passenger cars measured during low to moderate flows (up to 1,300 pcphpl). The free-flow speed can be estimated indirectly on the basis of the physical characteristics of the freeway segment. The physical characteristics include lane width, number of lanes, right-shoulder lateral clearance, and interchange density. Equation 6.1 is provided in the HCM 2000 for use in estimating the free-flow speed of a basic freeway segment under normal conditions:

$$FFS = BFFS - f_{LW} - f_{LC} - f_N - f_{ID} \tag{6.1}$$

where: FFS = free-flow speed (mph);

$BFFS$ = base free-flow speed, 70 mph (urban) or 75 mph (rural);

f_{LW} = adjustment for lane width (mph);

f_{LC} = adjustment for right-shoulder lateral clearance (mph);

f_N = adjustment for number of lanes (mph); and

f_{ID} = adjustment for interchange density (mph).

In this research, the rain adjustment factor will be used in a similar fashion to the adjustment factors in Equation 6.1 to estimate the average base speed under rain conditions. The rain adjustment factor will be determined as the difference between the average speed under normal conditions and the average speed under rain conditions. Equation 6.1, as presented in HCM 2000, is modified in Equation 6.2 and includes an additional factor to account for rain conditions as follows:

$$S_{Rain} = BFFS - f_{LW} - f_{LC} - f_N - f_{ID} - f_{Rain} = FFS - f_{Rain} \tag{6.2}$$

$$S_{Rain} = S_{Norm} - f_{Rain} \tag{6.3}$$

where: S_{Rain} = average speed under rain conditions (mph);

S_{Norm} = average speed under normal conditions (mph); and

f_{Rain} = adjustment factor due to rain (mph).

Equation 6.2 describes the average speed for rain conditions under low volume conditions. The equation estimates what could be considered to be the base speed under rain conditions. Equation 6.3 shows the approach to be taken to estimate the base speed under rain conditions. The base speed under rain conditions can be estimated as the average speed under normal conditions minus a rain adjustment factor. Thise chapter describes the development of this adjustment factor.

Speed-Flow-Precipitation Data

Using the speed-flow data gathered in this research for each precipitation level, the percentage reduction in the average speed under normal conditions as a result of rain is estimated. Table 6.1 summarizes the roadways under which speed-flow data were gathered for normal and rain conditions indicating each precipitation level. As the table shows, data were collected at six precipitation levels.

Table 6.1 Roadway at each precipitation level

Roadway	**Normal**	**Rain - Precipitation level[a]**					
		0.05	**0.07**	**0.16**	**0.22**	**0.23**	**0.24**
I-80	√	√		√			√
I-495	√						
Rte 3	√		√		√	√	
Rte 46	√		√				

a: inches/hr

Table 6.1 shows that I-80 and Route 3 have data under both rain and normal conditions. Although data are available for Route 46 under both normal and rain conditions, this data is not used in developing the rain adjustment factor. Figure 6.1 shows the speed-flow conditions on Route 46 under both rain and normal conditions. The average speed under normal conditions of 59.8 mph, is less than the average speed under rain conditions of 61.7 mph. For this reason the data for Route 46 are excluded for estimating the rain adjustment factors.

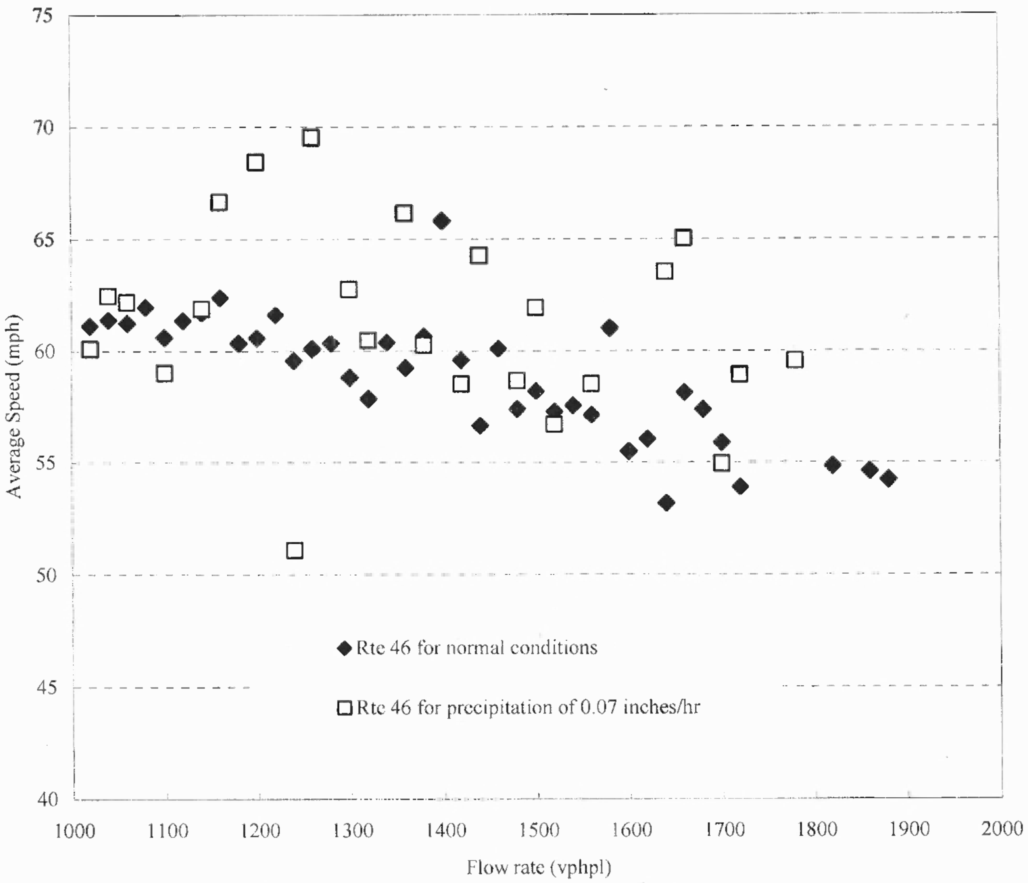

Figure 6.1 Speed-flow Scatter plot for Route 46

Hence, the two comprehensive data sets at I-80 and Route 3, were used in the estimation of the rain adjustment factor. The data indicated the five precipitation levels at 0.05, 0.07, 0.16, 0.22 and 0.24 inches/hr.

Average Speed at each flow level

Figure 6.2 shows the speed-flow scatter plot for I-80 under normal conditions and for precipitation levels, 0.05, 0.16 and 0.24 inches/hr.

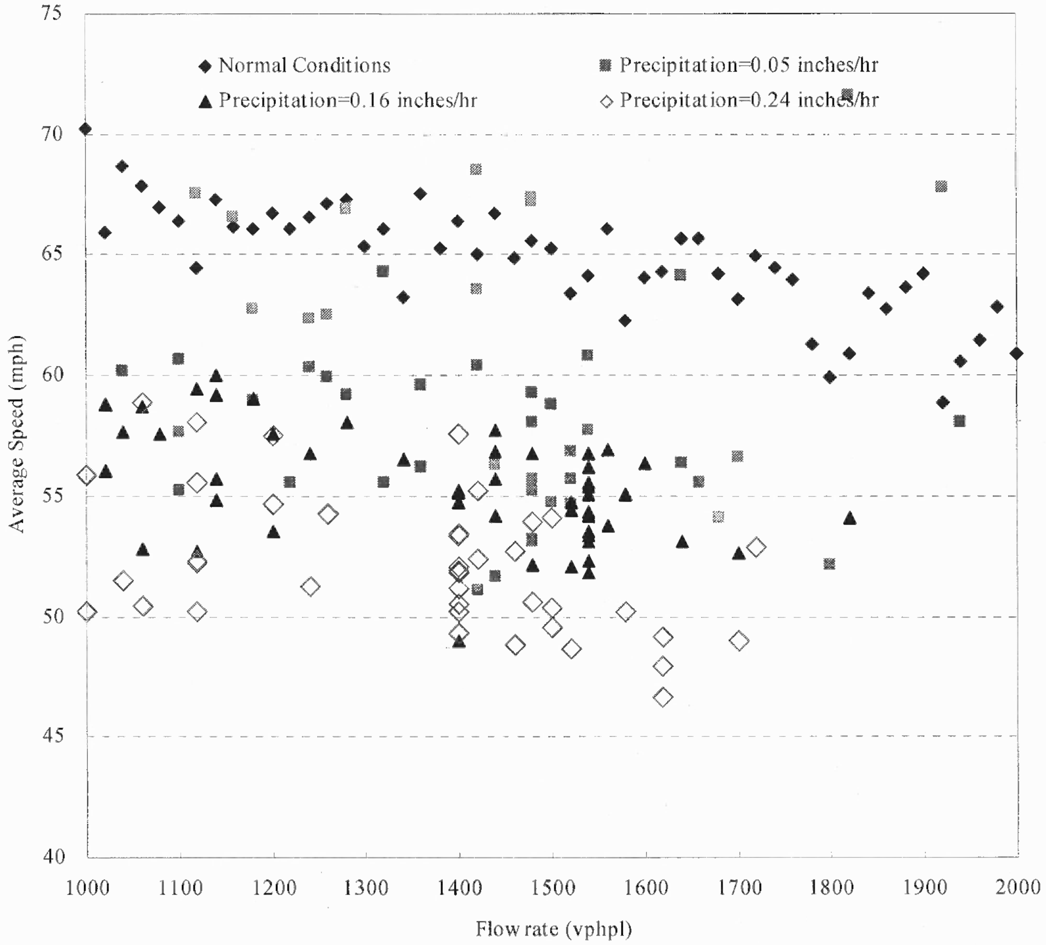

Figure 6.2 Speed-flow Scatter plot for I-80

Also, Figure 6.3 shows the speed-flow scatter plot for Route 3 under normal conditions and for precipitation levels, 0.07, 0.22 and 0.23 inches/hr. As the figure shows, the data under rain conditions are not continuous for all flow rates. Under normal conditions data are available for a wider ranges of the flow rate than they are for rain conditions. This lack of speed-flow data under rain conditions for a wide flow range made it difficult to provide comparisons between average speed under normal conditions and average speed under rain conditions.

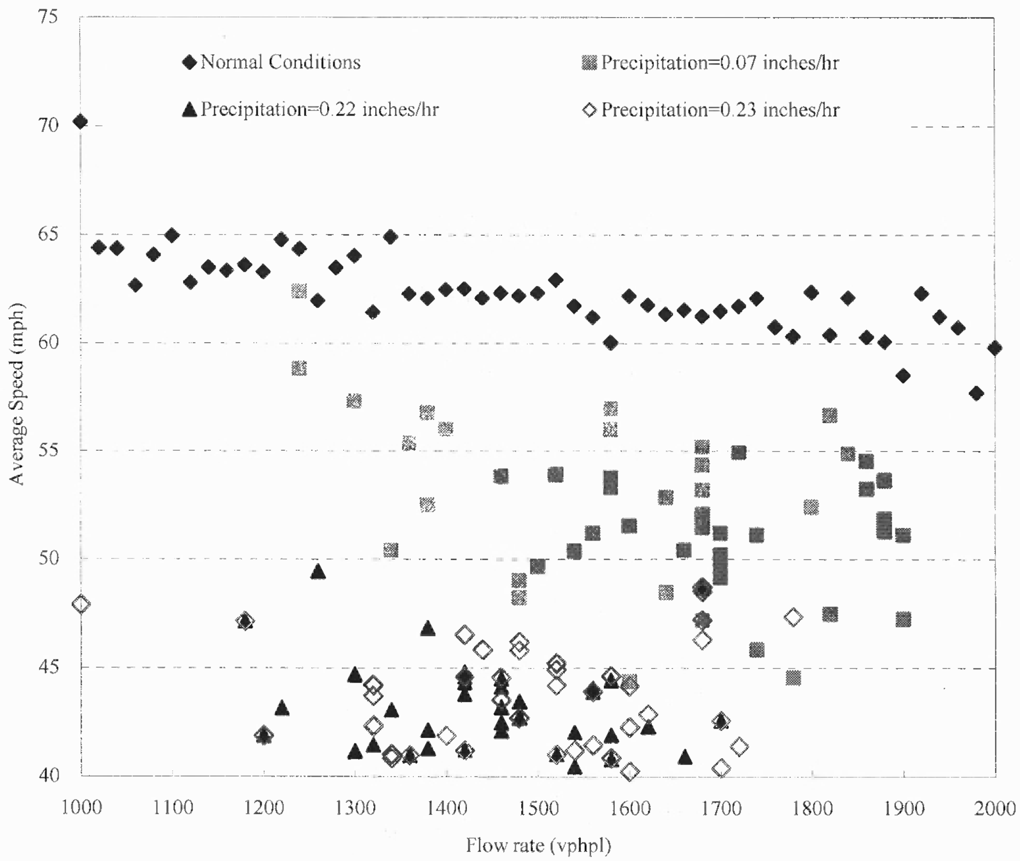

Figure 6.3 Speed-flow Scatter plot for Route 3

Under both rain and normal conditions, flow rates were grouped into 100 vphpl flow ranges from 1100-1200 vphpl to 1900-2000 vphpl. Figure 6.4 shows the speed-flow relationships at each precipitation level for I-80 and Route 3 using these flow ranges.

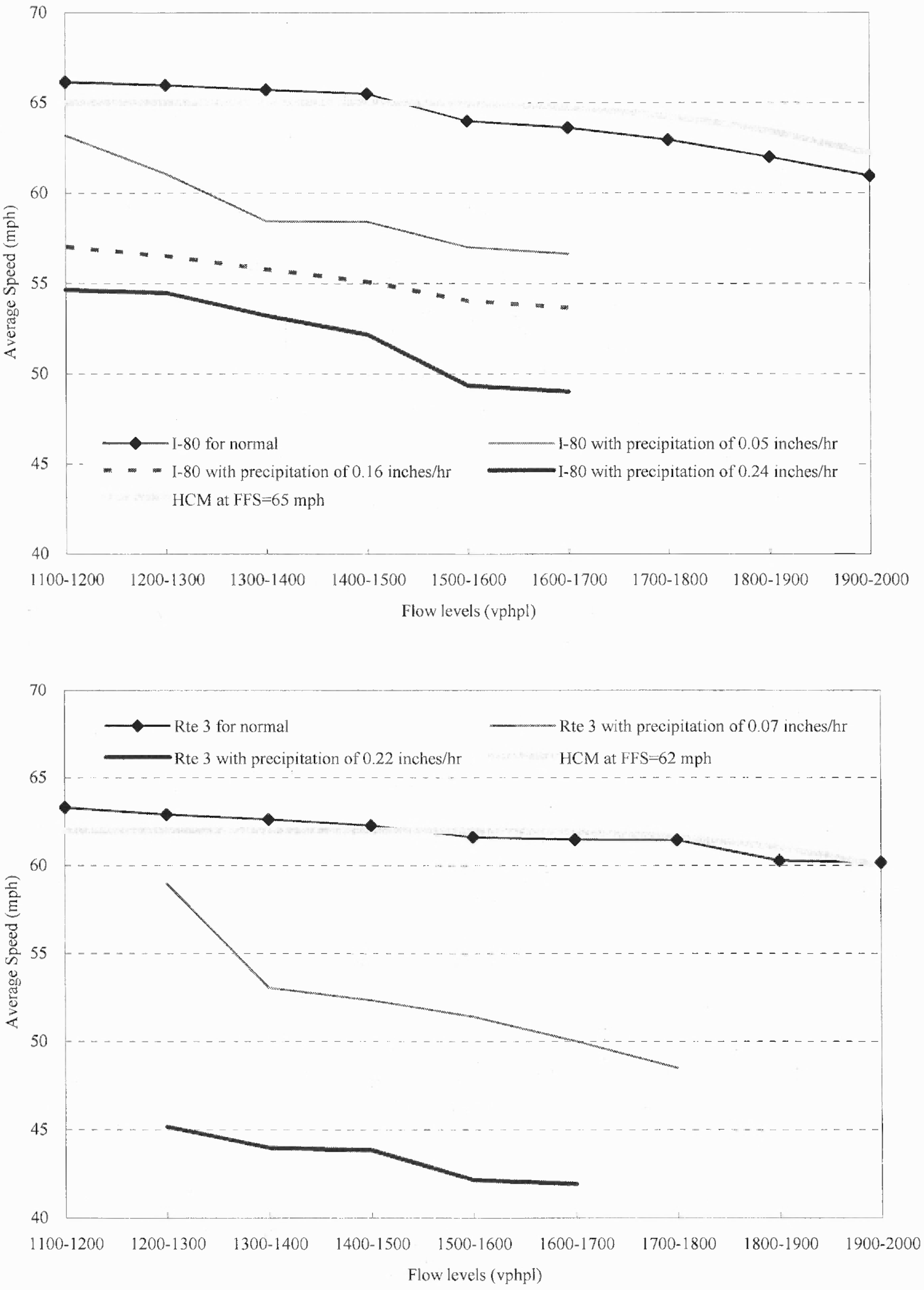

Figure 6.4 Speed-flow relationships for I-80 and Route 3

For I-80, under normal conditions the speed generally decreases for flow rates greater than 1400 vphpl. With a precipitation, speed is lower than the speed under normal conditions and generally decreases with increasing flow rate. Similarly for Route 3, under normal conditions the speed gradually decreases as the flow rate increases.

With precipitations of 0.22 and 0.24 inches/hr the average speed is less than 55 mph for both I-80 and Route 3. Under rain conditions, data were not gathered when the flow level is less than 1100 vphpl. The difference in the average speed under normal conditions and under rain conditions for precipitation levels greater than 0.2 inches/hr ranged from 10 to 15 mph when the flow level is 1100-1200 vphpl. This indicates a large speed reduction under rain conditions at low flow rates when the precipitation levels are greater than 0.2 inches/hr.

6.3 Rain Adjustment Factors using I-80 and Route 3

Using Equations 6.2 and 6.3, rain adjustment factors were developed as the difference in speed between average speeds under normal conditions and average speeds under rain conditions. Figure 6.5 shows the approach taken in estimating the rain adjustment factor. The speed differences, or rain adjustment factors, are estimated at each flow level.

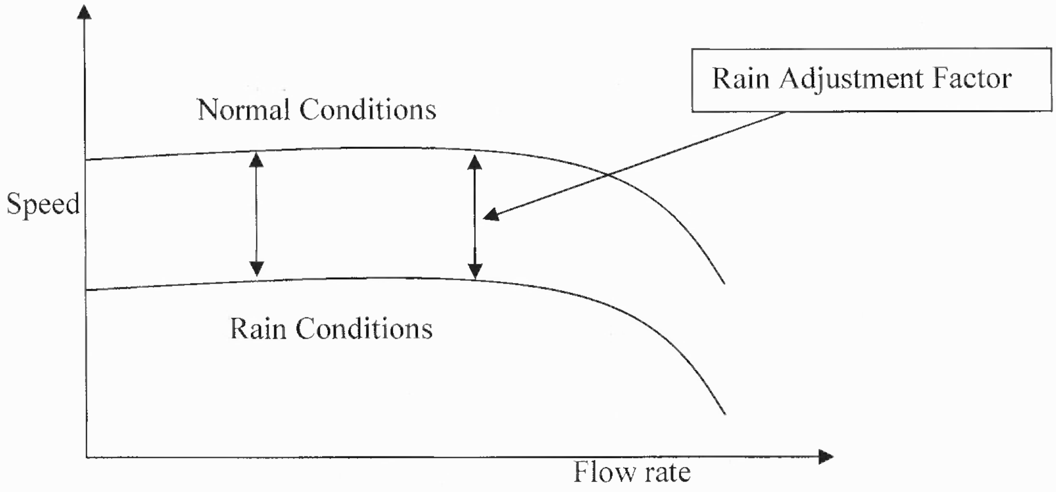

Figure 6.5 Example of Rain Adjustment Factor in the speed-flow relationships

Table 6.2 shows the percentage reduction in the normal speed under rain conditions at each flow range and Table 6.3 shows the rain adjustment factors. The percentage reduction in the average speed is calculated as the difference in the average speed under normal conditions and under rain conditions divided by the speed under normal conditions. It is assumed that this reduction in speed would be consistent at similar roadways in the State of New Jersey as well as outside New Jersey. The detailed procedure for using this adjustment factor to estimate the average speed under rain conditions is discussed in a case study that is presented later in this Chapter. Under normal conditions the speed on I-80 is 66.2 mph with a flow rate between 1100 and 1200 vphpl. Under rain conditions, with a precipitation level of 0.05 inches/hr, speed is reduced by 4-5% or to 63.2 mph, as shown in Table 6.2. The table shows that there is a greater percentage reduction of speeds when the flow rate is greater than 1300 vphpl. This increase in the percentage reduction exists for precipitation levels of 0.05 and 0.16 inches/hr on I-80. There is a greater percentage reduction of speeds when the flow rate is greater than 1500 vphpl. This increase in the percentage reduction exists for precipitation levels of 0.22 inches/hr on Route 3.

Table 6.2 Percentage Reduction of the normal speed under rain conditions

Precipitation[a] / Flow levels[b]	I-80 Percentage Speed Reduction			Rte 3 Percentage Speed Reduction	
	0.05 (Light)	**0.16 (Medium)**	**0.24 (Heavy)**	**0.07 (Light/medium)**	**0.22 (Heavy)**
1100-1200	4.5%	13.8%	17.4%	NA	NA
1200-1300	7.5%	14.3%	17.4%	6.3%	28.2%
1300-1400	10.5%	15.1%	19.0%	15.3%	29.5%
1400-1500	10.8%	15.5%	20.3%	16.0%	29.6%
1500-1600	10.9%	15.5%	22.9%	16.6%	31.6%
1600-1700	11.0%	15.6%	22.9%	18.7%	31.8%

a: inches/hr; b: vphpl

Table 6.3 Rain Adjustment Factors at each flow level

Precipitation[a] / Flow levels[b]	I-80 Rain Adjustment Factors			Rte 3 Rain Adjustment Factors	
	0.05 (Light)	**0.16 (Medium)**	**0.24 (Heavy)**	**0.07 (Light/medium)**	**0.22 (Heavy)**
1100-1200	3.0 mph	9.1 mph	11.5 mph	NA	NA
1200-1300	4.9 mph	9.5 mph	11.5 mph	4.0 mph	17.7 mph
1300-1400	6.9 mph	9.9 mph	12.5 mph	10.0 mph	18.5 mph
1400-1500	7.1 mph	10.2 mph	13.3 mph	10.0 mph	18.5 mph
1500-1600	7.0 mph	10.0 mph	14.6 mph	10.2 mph	19.5 mph
1600-1700	7.0mph	10.0 mph	14.6 mph	11.5 mph	19.6 mph

a: inches/hr; b: vphpl

Table 6.3 shows that on I-80 with a precipitation level of 0.24 inches/hr the rain adjustment factor increases when the flow rate increases. This is also true on Route 3 for precipitation levels of 0.07 and 0.22 inches/hr. Although the rain adjustment factors are developed using data from I-80 and Route 3, these factors for roadways calculated in New Jersey and in other States.

6.4 Rain Adjustment Factors using the speed-flow model

In sections 6.2 and 6.3 the rain adjustment factors were developed using I-80 and Route 3 data for different flow rates. In this section a second approach for developing rain adjustment factors is discussed. The approach taken is through the use of the speed-flow model developed in Chapter 4. The speed-flow model developed in Chapter 4 is: $S = 64.9 - 2.3*10^{-6}F^2 - 53.6P$. The model is a function of the flow rate and the precipitation level. From this model, Equation 6.4 can be used to estimate the rain adjustment factor. Similar to the rain adjustment factor developed in the previous chapter, the rain adjustment factor is the speed difference between speed under clear weather conditions and speed under rain conditions.

$$f_{Rain} = 53.6P \qquad (6.4)$$

where: P = precipitation level (inches/hr)

The rain adjustment factor shown in equation 6.4 is a function of the precipitation level. Table 6.4 shows the rain adjustment factor using Equation 6.4 for four precipitation levels.

Table 6.4 Rain Adjustment Factors using the speed-flow model

Precipitation (inches/hr)	f_{Rain} (mph)
0.05	2.68
0.10	5.36
0.15	8.04
0.20	10.72

6.5 Case Study for Route 4

6.5.1 Introduction

In this section, using the HCM 2000 model along with the rain adjustment factors the average speed under rain conditions will be obtained for a sample roadway, Route 4 in northern New Jersey.

HCM 2000 provided a procedure to estimate the free-flow speed and the average speed under clear weather conditions. Under clear weather conditions the free-flow speed is estimated using Equation 6.1. The free-flow speed is also estimated using Equation 6.5 for the speed and flow rate conditions shown in the equation. The average speed or speed under flow conditions in HCM 2000 is estimated using Equations 6.6 and 6.7. S, F, and FFS represent the average speed, the flow rate and the free-flow speed respectively in Equations 6.5, 6.6, and 6.7. Equation 6.6 and 6.7 are used for estimating the average speed under clear weather conditions for different free-flow speeds and flow rates.

$$S = FFS \tag{6.5}$$

where: 55<FFS<75 mph and F<(3400-30FFS)

$$S = FFS - \left[\left(FFS - \frac{160}{3} \right) \left(\frac{F + 30FFS - 3400}{30FFS - 1000} \right)^{2.6} \right] \tag{6.6}$$

where: 70<FFS<75 mph and (3400-30FFS)<F<2400

$$S = FFS - \left[\frac{1}{9} (7FFS - 340) \left(\frac{F + 30FFS - 3400}{40FFS - 1700} \right)^{2.6} \right] \tag{6.7}$$

where: 55<FFS<70 mph and (3400-30FFS)<F<(1700+10FFS)

After estimating the free-flow speed and average speed under clear weather conditions using the equations, the percentage reduction of the average speed under rain conditions in Table 6.2 can be used for estimating the rain adjustment factors at each precipitation and flow level. The procedure for estimating the rain adjustment factors is as follows.

- Estimate the free-flow speed using Equations 6.1.
- Estimate the average speed using either Equation 6.5, 6.6 or 6.7.
- Estimate the rain adjustment factors using Table 6.2.

Using the rain adjustment factors, the average speed under rain conditions can be determined when the flow rate is less than 1700 vphpl. The limitation is due to the fact that the speed data under rain conditions were gathered when the flow rate ranged from 1100 to 1700 vphpl.

6.5.2 Description of Route 4

Route 4 was selected to perform a case study to investigate the impact of the rain adjustment factors on the estimate of speed. Route 4 is an Urban Freeway/Expressway located in Bergen County. The roadway consists of six lanes with three lanes is each direction, with a posted speed limit of 50 mph. There are 12-foot lanes, roadside obstructions located 10 feet from the travel lane on the right, and within two miles of the segment there are 3 interchanges. Table 6.5 shows the physical characteristics of I-80, Route 3 and Route 4. The speed limit is 50 mph for Route 3 and Route 4. There are three lanes in each direction for I-80 and Route 4.

Table 6.5 Physical Charateristics of I-80, Route 3 and Route 4

Sites	Functional Classifications	No. of Lanes	Speed Limit
I - 80	Urban Interstate	3	55 mph
Rte 3	Urban Freeway/Expressway	4	50 mph
Rte 4	Urban Freeway/Expressway	3	50 mph

6.5.3 Estimating Speed

In this section the speeds under clear weather are estimated using HCM 2000 and the speeds under rain conditions are estimated using the HCM 2000 along with the rain adjustment factors.

HCM FFS and Average Speed for Route 4

The calculation of the free-flow speed for Route 4 is as follows.

$$FFS = BFFS - f_{LW} - f_{LC} - f_N - f_{ID} = 70 - 0 - 0 - 3 - 5 = 62\,mph$$

Where: $BFFS$ =70 mph for an urban area;

f_{LW}=0.0 (12-foot lanes);

f_{LC}=0.0 (10-foot shoulder on right);

f_N=3.0 (3 lanes in one direction); and

f_{ID}=5 $\left(\dfrac{3}{2\,miles} = 1.5\,interchange/mi\right)$.

Since the free-flow speed is 62 mph, the average speed can be determined using Equation 6.7 for free-flow speeds between 55 and 70 mph. The HCM 2000 suggests reductions of the average speed under clear weather conditions in the range of 4.8% to 6.4 % to determine the average speed under heavy rain conditions. Light rain does not have much effect on the average speed although the HCM does not state the definition of light rain and heavy rain. The free-flow speed and the average speed under clear weather and heavy rain conditions using the HCM 2000 for Route 4 are shown in Table 6.6.

Under heavy rain conditions, average speeds are reduced by 4.8% to 6.4 %. As the table shows, the average speed under heavy rain conditions with a flow level of 1100-1200 vphpl, which is 58 or 59 mph, is calculated as the free-flow speed multiplied by the percentage reduction or 62 mph times (1 - 0.048) or (1 - 0.064).

Table 6.6 Estimated Speeds in HCM 2000: clear weather and rain conditions on Route 4

Conditions / Flow rate (vphpl)	Clear weather Conditions		Heavy Rain Conditions
	FFS (mph)	Avg. Speed (mph)	Avg. Speed (mph)
1100-1200	62.0	-	58.0 ~ 59.0
1200-1300	62.0	-	58.0 ~ 59.0
1300-1400	62.0	-	58.0 ~ 59.0
1400-1500	62.0	-	58.0 ~ 59.0
1500-1600	62.0	-	58.0 ~ 59.0
1600-1700	-	61.9	58.0 ~ 59.0
1700-1800	-	61.7	57.7 ~ 58.7
1800-1900	-	61.1	57.1 ~ 58.1
1900-2000	-	60.0	56.2 ~ 57.2
2000-2100	-	58.5	54.8 ~ 55.7
2100-2200	-	56.5	52.9 ~ 53.8
2200-2300	-	53.8	50.4 ~ 51.2
2300-2400	-	-	-

Average Speed using the Rain Adjustment Factors for Route 4

Average speeds under rain conditions were then estimated using the rain adjustment factors developed in this research. Table 6.7 shows the average speeds for Route 4 using the rain adjustment factors developed in this section. The table provides the average speeds for light, medium and heavy precipitation levels and for a wide range of flow rates.

Table 6.7 Average Speeds using Rain Adjustment Factors on Route 4

Precipitation[a] / Flow rate[b]	Avg. Speed on Route 4 using I-80 Rain Adjustment Factors[c]			Avg. Speed on Route 4 using Rte 3 Rain Adjustment Factors[c]	
	0.05 (Light)	**0.16 (Medium)**	**0.24 (Heavy)**	**0.07 (Light/medium)**	**0.22 (Heavy)**
1100-1200	59.2	53. 5	51.2	NA	NA
1200-1300	57.4	53. 1	51.2	58.1	44.5
1300-1400	55.5	52.6	50.2	52.5	43.5
1400-1500	55.3	52.4	49.4	52.1	43.5
1500-1600	55.2	52.4	47.8	51.7	42.4
1600-1700	55.1	52.2	47.6	50.3	42.2

a: inches/hr; b: vphpl; c: mph

Rain adjustment factors are developed using data gathered for both I-80 and for Route 3. For example, using I-80 rain adjustment factor, the average speed with a flow level of 1100-1200 vphpl when the precipitation level is 0.05 inches/hr is calculated as the free-flow speed, 62 mph, multiplied by the percentage reduction of the normal speed under rain conditions. The percentage reduction of normal speed under rain conditions is 4.5% when the precipitation level is 0.05 inches/hr and the flow rate is between 1100 and 1200 vphpl. For this example, the average speed under rain conditions, which is 59.2 mph, is when 62 mph times (1 - 0.045). Using the Route 3 rain adjustment factor, the average speed with a flow level of 1600-1700 vphpl when the precipitation level is 0.07 inches/hr is calculated as the average speed, 61.9 mph, multiplied by the percentage reduction of the normal speed under rain conditions. The percentage reduction of normal speed under rain conditions is 18.7% when the precipitation level is 0.07 inches/hr and the flow rate is between 1600 and 1700 vphpl. For this example, the average speed under rain conditions, which is 50.3 mph, is when 61.9 mph times (1 - 0.187).

Using the rain adjustment factors, the average speed ranges from 55 to 59 mph with a precipitations level of 0.05 inches/hr when the flow rate is less than 1700 vphpl in Table 6.7. Using HCM 2000 the average speeds under heavy rain conditions ranges from 57 to 59 mph when the flow rate is less than 1700 vphpl as shown in Table 6.6.

Comparison of Speeds

Figures 6.6 show the estimated speed under clear weather and rain conditions using HCM 2000 and the average speed under rain conditions using the I-80 and Route 3 rain adjustment factors for Route 4. The average speed in HCM 2000 under heavy rain conditions decrease when the flow rate is greater than 1600 vphpl.

The speed with a precipitation of 0.05 inches/hr using the I-80 rain adjustment factors decreases slightly when the flow rate is greater than 1300 vphpl. The speeds with a precipitation of 0.16 inches/hr using the I-80 rain adjustment factors decrease slightly when the flow level increases. The speed with a precipitation of 0.24 inches/hr using the I-80 rain adjustment factors decrease slightly when the flow rate is greater 1500 vphpl. The speed difference between the average speed with a precipitation of 0.05 and 0.24 inches/hr is about 10 mph when the flow level is 1100-1200 vphpl. The average speeds using the rain adjustment factors with a precipitation level of 0.05 inches/hr and the average speed using the HCM model for heavy rain difference are similar when the flow level is 1100-1200 vphpl. The average speeds under heavy rain conditions for HCM 2000 are greater than the average speeds using the rain adjustment factors.

Using the Route 3 rain adjustment factors, the speed with a precipitation level of 0.07 inches/hr decreases slightly when the flow rate is greater than 1300 vphpl.

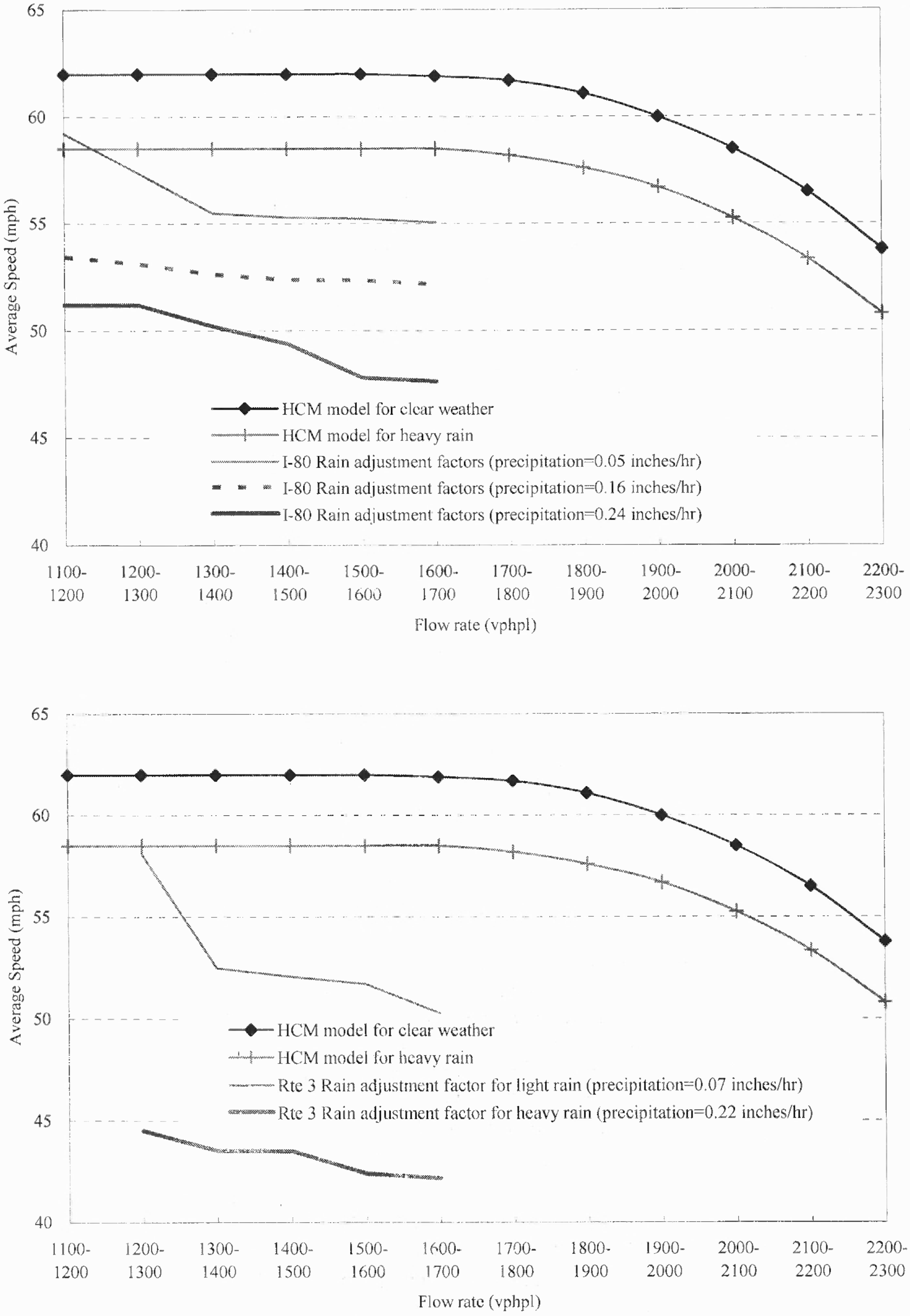

Figure 6.6 HCM 2000, the I-80 and Rte 3 Rain Adjustment Factors for Route 4

The speeds using the Route 3 rain adjustment factors with a precipitation of 0.22 inches/hr decrease slightly when the flow level increases. The rain adjustment factors fit better when the flow ranges from 1100 to 1700 vphpl, the number of lane each direction are 3-4 lanes, the speed limit ranges from 50 to 55 mph and the free-flow speed ranges from 55 to 70 mph. Using the rain adjustment factors of I-80 and Route 3 data the findings are as follows.

Table 6.8 shows the rain adjustment factor comparisons using the HCM 2000, the speed-flow model, and the HCM 2000 along with the rain adjustment factor of I-80 data. The speed reductions of normal speed under rain conditions using the HCM 2000 are less than these using the HCM 2000 model along with the rain adjustment factors. The rain adjustment factors using HCM 2000 and the speed-flow model are the only ones related to precipitation levels. Under medium and heavy rain conditions the rain adjustment factors using the speed-flow model and the HCM 2000 along with rain adjustment factors of I-80 data are similar.

Table 6.8 Rain Adjustment Factor Comparisons on Route 4

Precipitation (inches/hr)	Flow rate (vphpl)		f_{Rain} for HCM2000 (mph)	f_{Rain} in speed-flow model (mph)	f_{Rain} using HCM 2000 along with rain adjustment factors of I-80 data (mph)
0.05 (Light rain)	Low	>1200	NA	2.7	2.8
	Medium	1650		2.7	6.7
	High	2000		2.7	NA
0.16 (Medium rain)	Low	>1200	NA	8.6	8.5
	Medium	1650		8.6	6.7
	High	2000		8.6	NA
0.24 (Heavy rain)	Low	>1200	3.0 ~ 4.0	12.9	10.8
	Medium	1650	3.0 ~ 4.0	12.9	14.1
	High	2000	3.0 ~ 4.0	12.9	NA

Figure 6.6 shows that the average speed in HCM 2000 under normal and rain conditions decreases significantly at high flow. Using the rain adjustment factors the average speed under rain conditions decreases significantly at low/medium flow rates.

Third, the rain adjustment factors are developed using I-80 and Route 3 data. I-80 rain adjustment factors can be better fitted than Route 3 rain adjustment factors under rain conditions. Route 3 intersects with Route 1 and I-495. The congestion on I-495, which access the Lincoln Tunnel (a major tunnel providing access to Manhattan), can cause the high speed reductions on Route 3 under rain conditions.

CHAPTER 7

CONCLUSIONS AND FUTURE RESEARCH

7.1 Results and Findings

This research developed speed-flow relationships that can be used under clear weather, rain and congested conditions. The research used a regression analysis approach to predict the speed-flow relationship for these conditions. In addition rain adjustment factors were developed to estimate more accurately the average speed at each flow level for rain conditions.

The existing speed-flow model in the Highway Capacity Manual (HCM, 2000) does not quantify the impact of rain and congested conditions on the estimate of speed. There are two different speed-flow models used in the HCM (2000) for clear weather conditions. These models include: (1) a speed-flow model when the range of free-flow speed is greater than 70 mph; and (2) a speed-flow model when the range of free-flow speed is less than 70 mph. In this research, the speed-flow model and the rain adjustment factors were developed when the range of free-flow speed is less than 70 mph. The speed-flow model was used to determine both the impact of rain and the impact of congested conditions while the rain adjustment factors were used to determine the impact of rain when the flow rate increases. In summary, the research results are as follows:

- The speed-flow model can be used to describe conditions under clear weather, rain, and congested conditions. The model reflects the fact that as flow increases, speed decreases under clear weather and rain conditions. Under congested conditions speed and flow operate on the lower or congested portion of the speed-flow model. In this case, as more vehicles are added, the discharge flow decreases and the speed also decreases. The speed under rain and congested conditions increases more than the speed under congested conditions.

- Under rain conditions the average speed decreases by about 0.05 mph when the precipitation level increases at 0.01 inches/hr.
- Both the speed-flow model developed in this research and the HCM (2000) show that the average speed under rain conditions seems to decrease slowly when the flow rate is less than 2000 vphpl. However, the rain adjustment factors, developed using individual roadways reflect the fact that the average speed under rain conditions seems to decrease significantly at low to medium flows and decreases slowly at medium to high flows.

7.2 Research Contributions

The objective of this research was to determine the impact of rain and congested conditions on the speed-flow relationship and to develope a speed-flow model for estimating operating speed under these conditions for New Jersey freeways. The speed-flow model developed in the research was validated using data not used in developing the speed-flow model and obtained from freeways in New Jersey. In the case study performed in the research the average speed under rain conditions was estimated using the rain adjustment factors and the speed-flow model. The results show that the average speeds under rain conditions using the rain adjustment factors and the speed-flow model are similar. The results of the research show that the speed-flow model can be used to demonstrate the overall relationship between speed and flow rate under clear weather, rain and congested conditions. The rain adjustment factors were also proven to be an accurate approach for determining the speed-flow relationship at each flow level.

In this research the speed-flow model for rain and congested conditions were developed quantitatively, which has not been done by previous investigators. In addition different rain adjustment factors were developed at each flow level. For rain conditions, the use of rain adjustment factors resulted in a more accurate speed-flow relationship.

The result of this research will be used to improve the speed-flow relationship provided in the HCM (2000). In addition, the analytical results from this research will be useful to transportation system practitioners in determining operating conditions under rain and congested conditions.

7.3 Recommendations for Future Research

In this research a speed-flow model and rain adjustment factors were developed using data collected during the peak period. For future study, a more accurate estimation of the speed-flow model can be developed by including off-peak period data. Incorporating more variables can also enhance the precision of the model. For example, the density of interchanges can be an important factor for estimating the speed-flow model and the drivers' visibility for estimating the average speed under rain conditions. The rain adjustment factors in this research have a limitation for estimating the average speed under rain conditions for other roadways, because the rain adjustment factors were developed using an individual roadway. Data from a variety of roadways (more than two roadways) for each precipitation level would be required to enhance the accuracy of the rain adjustment factors. In addition, the equivalent intervals of precipitation levels can increase the accuracy of the average speed estimate at each flow level.

APPENDIX SPEED-FLOW MODELS

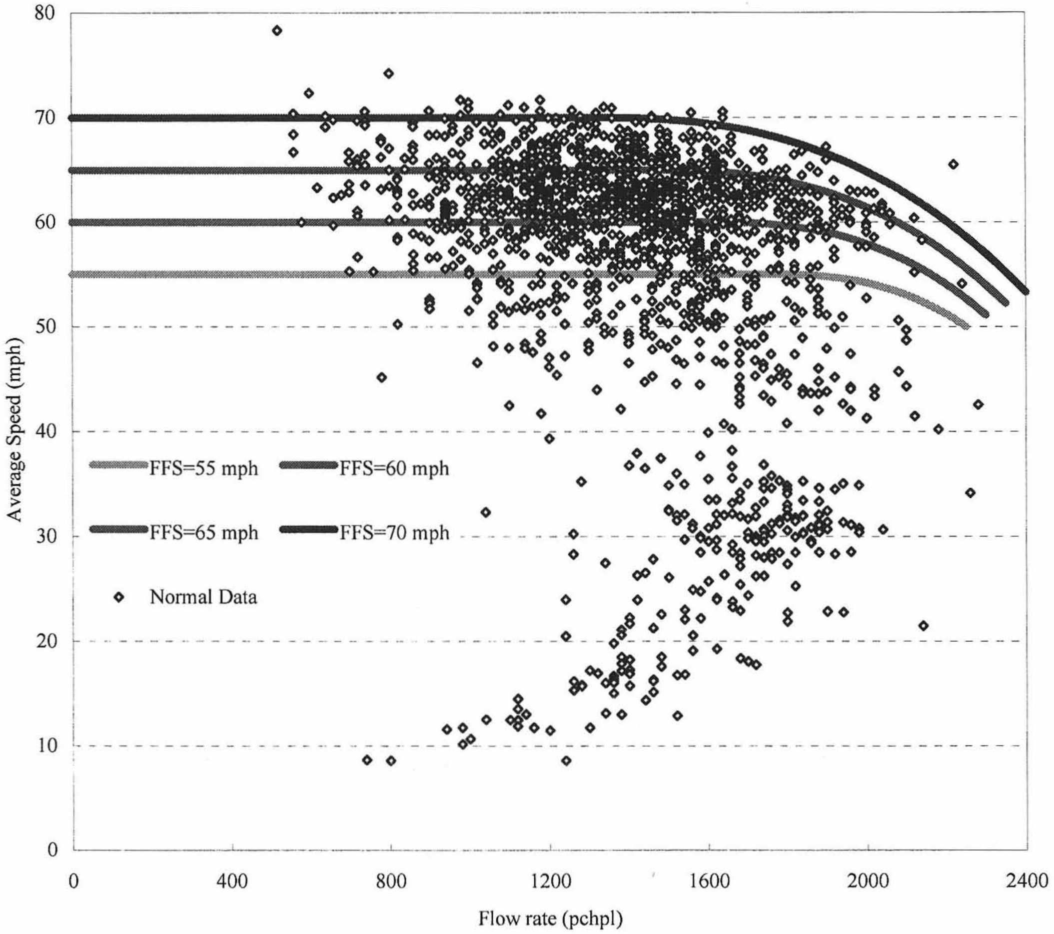

Figure A.1 Speed-Flow Models in HCM 2000 and Data for Normal conditions

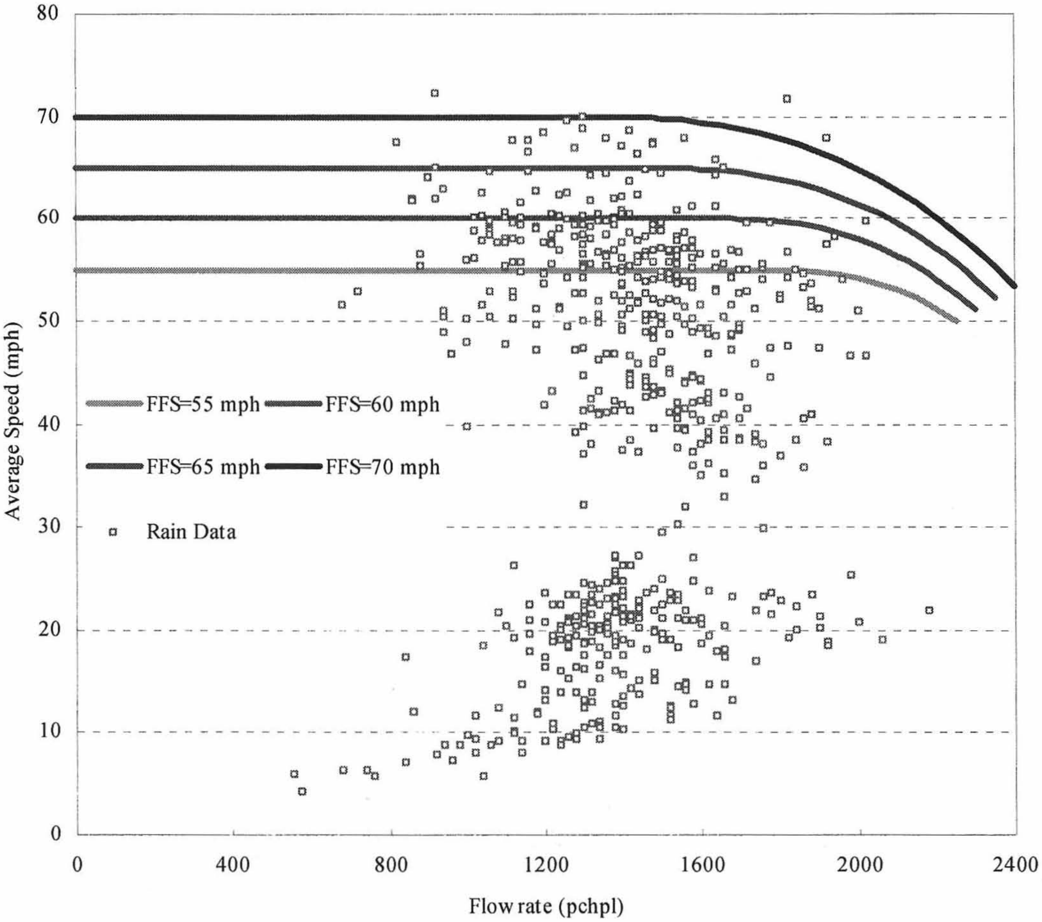

Figure A.2 Speed-Flow Models in HCM 2000 and Data for Rain conditions

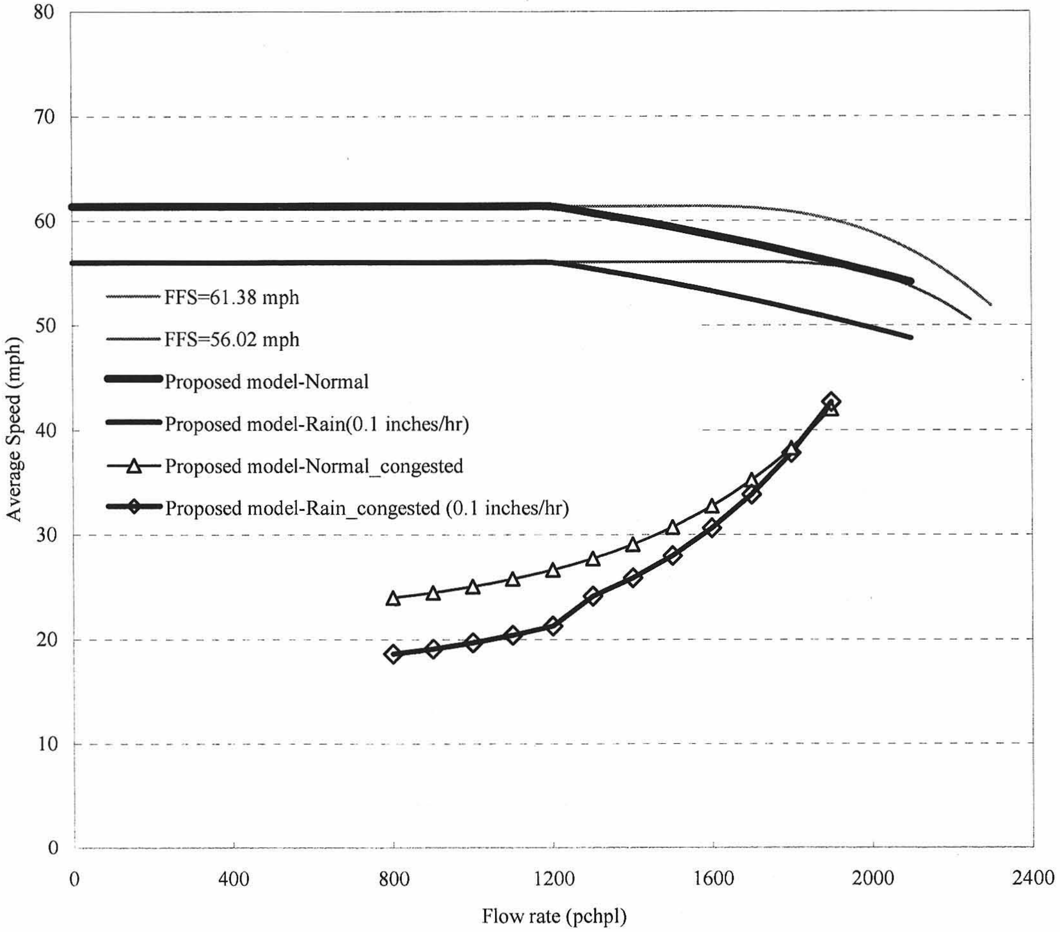

Figure A.3 Speed-Flow Models in HCM 2000 and the Proposed Models

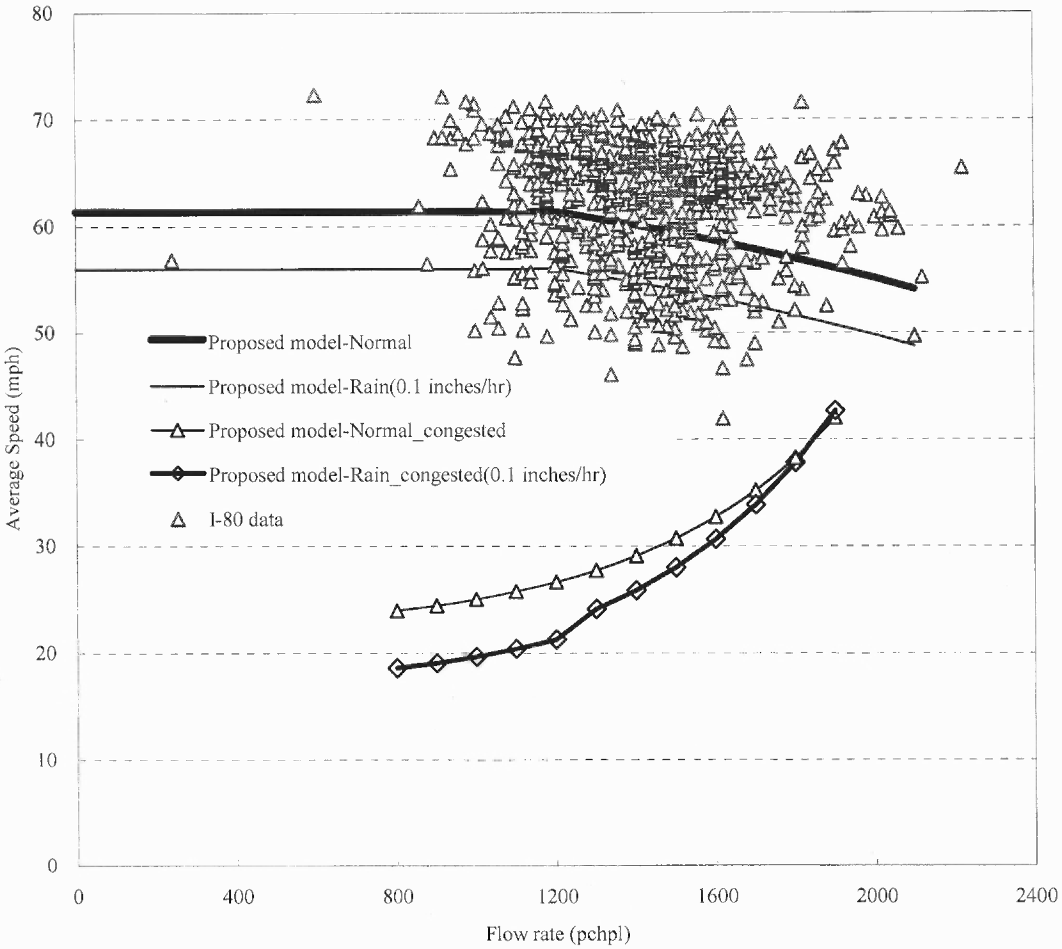

Figure A.4 Proposed Model and I-80 Data

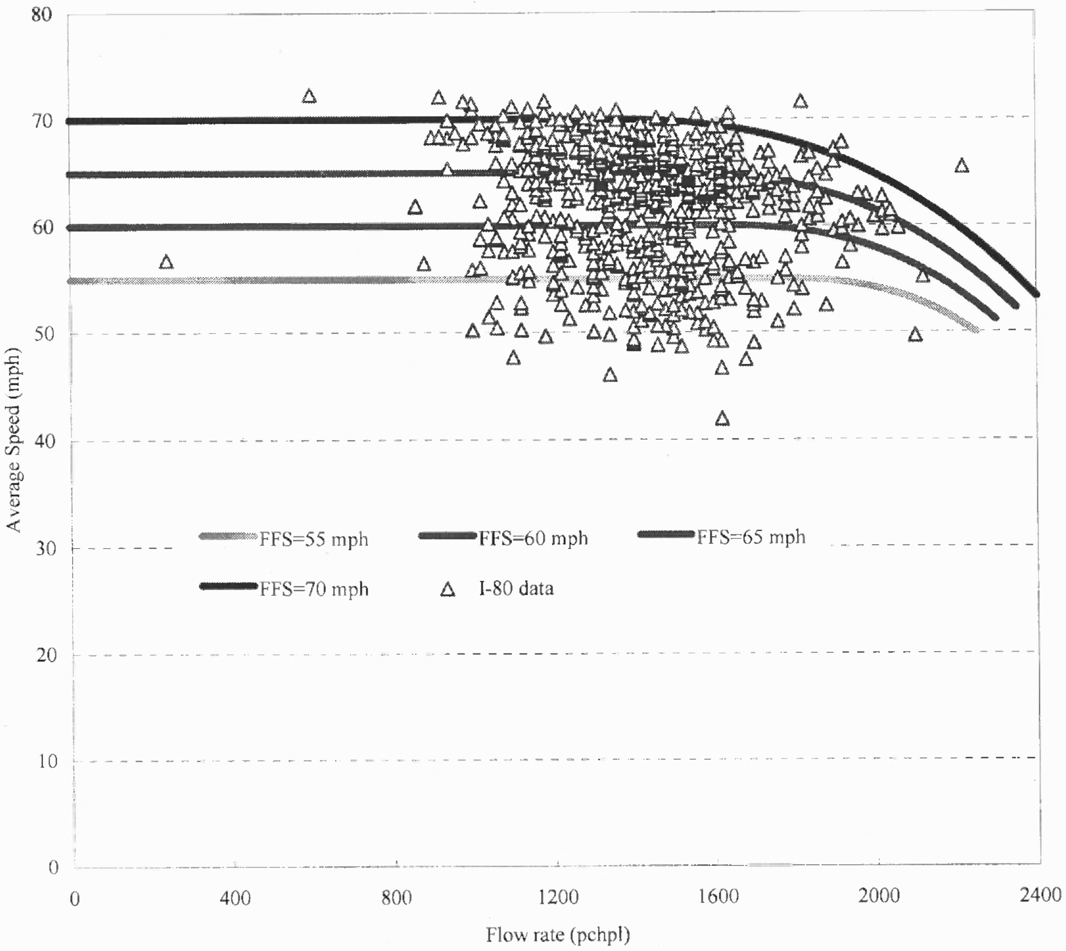

Figure A.5 Speed-Flow Models in HCM 2000 and I-80 Data

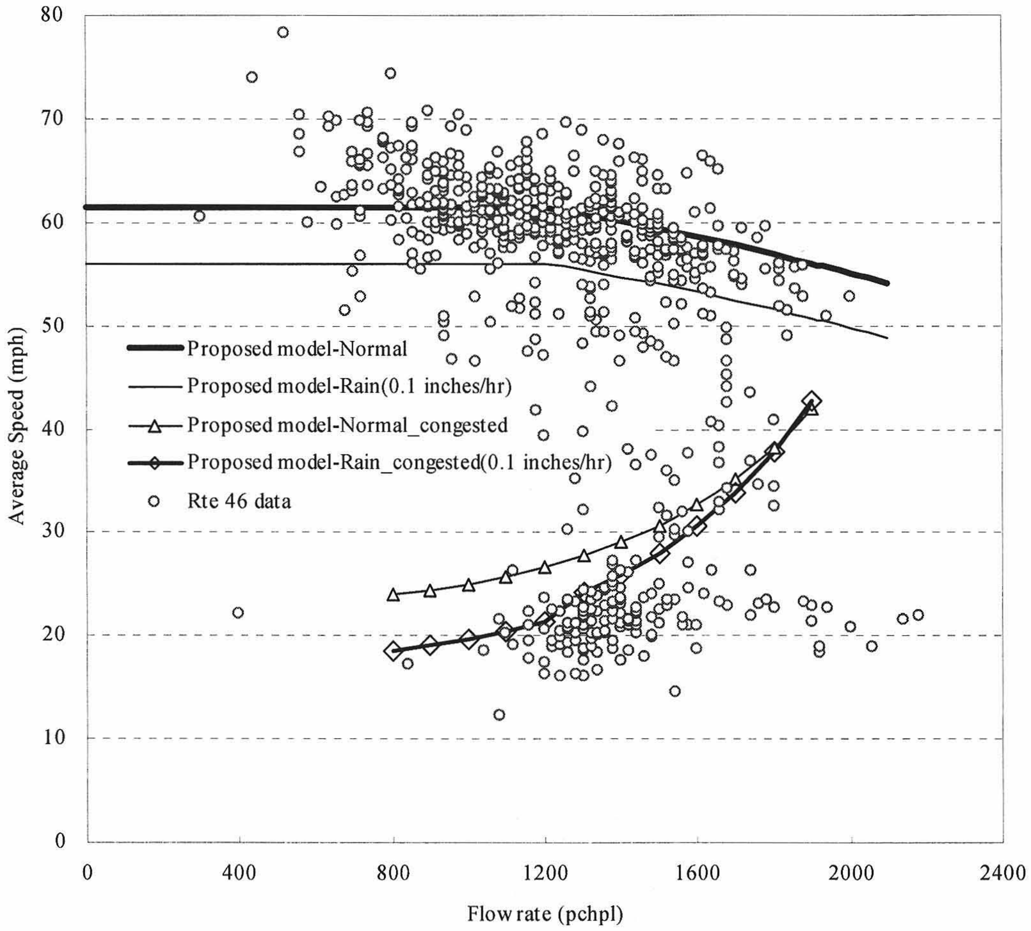

Figure A.6 Proposed Model and Rte 46 Data

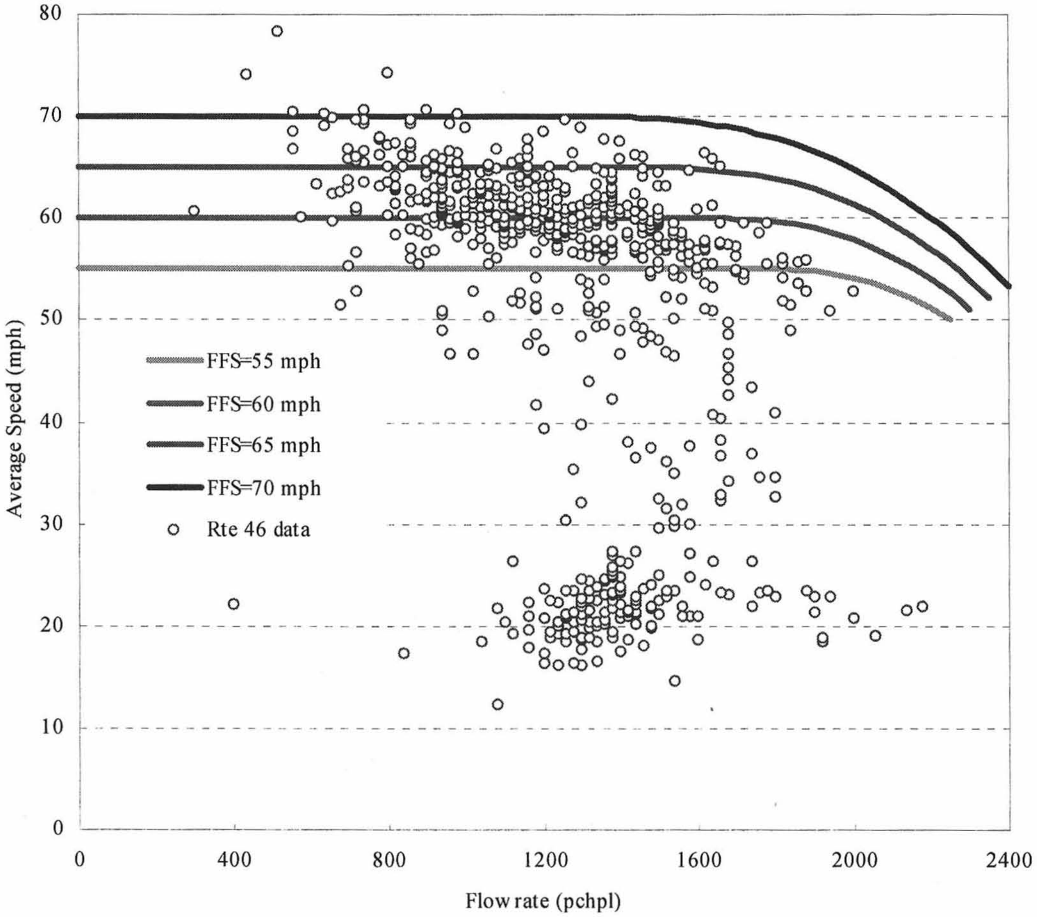

Figure A.7 Speed-Flow Models in HCM 2000 and Rte 46 Data

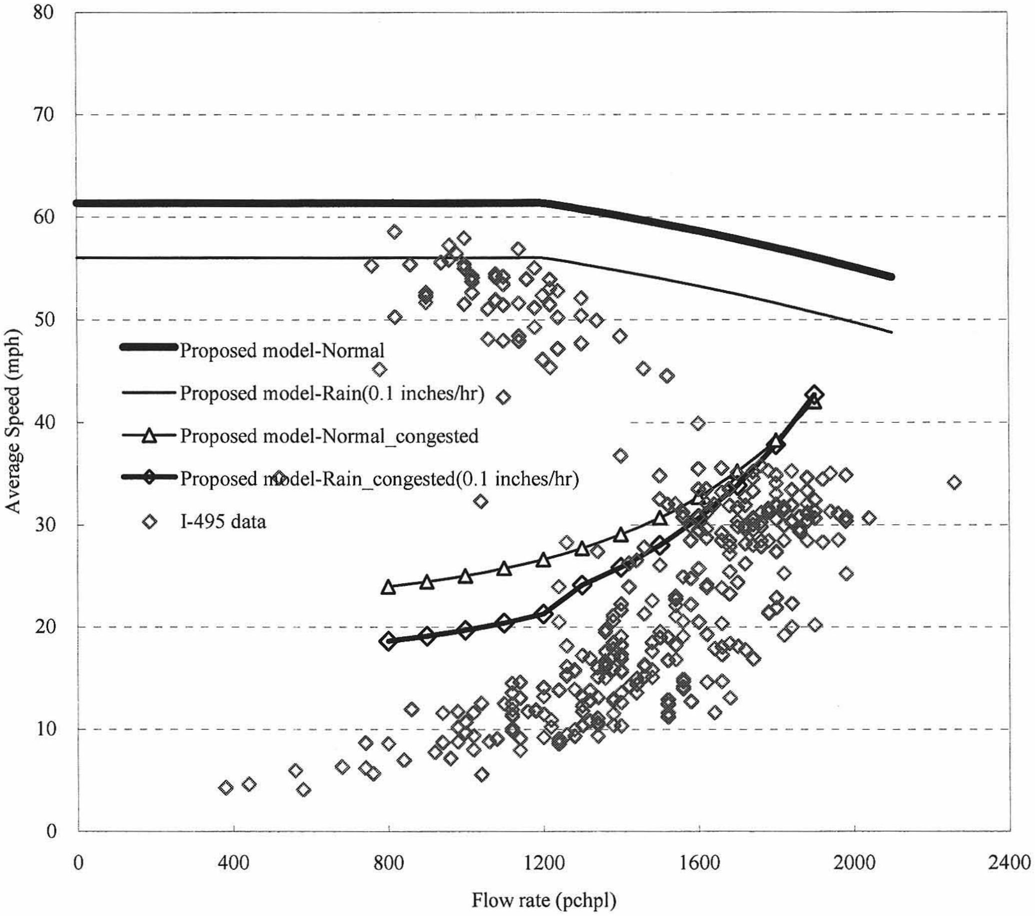

Figure A.8 Proposed Models and I-495 Data

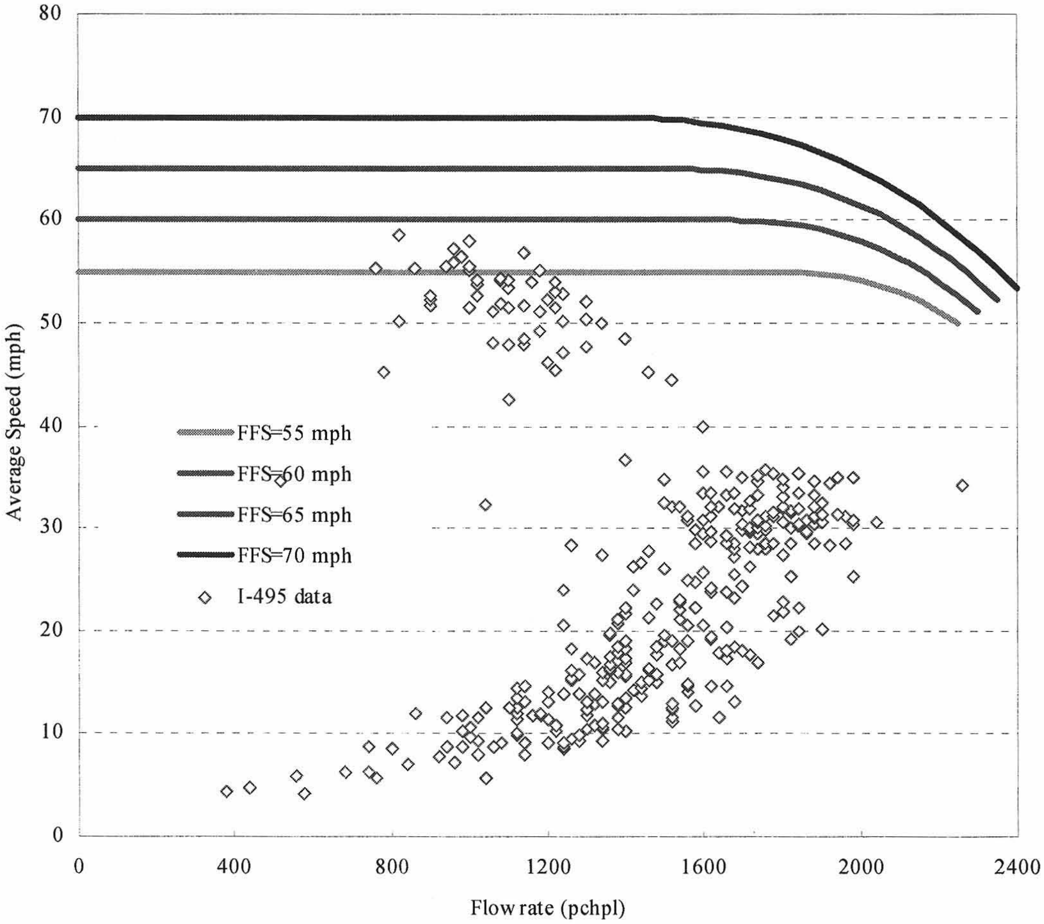

Figure A.9 Speed-Flow Models in HCM 2000 and I-495 Data

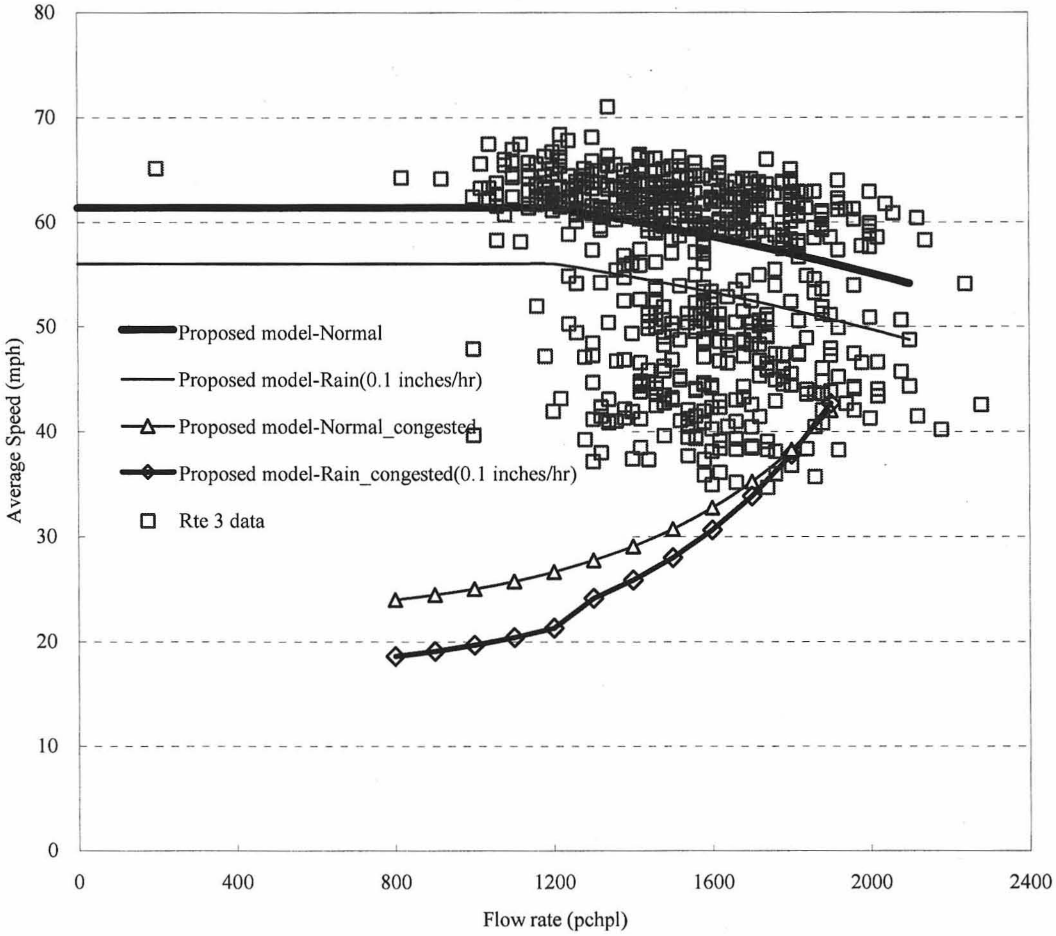

Figure A.10 Proposed Models and Rte 3 Data

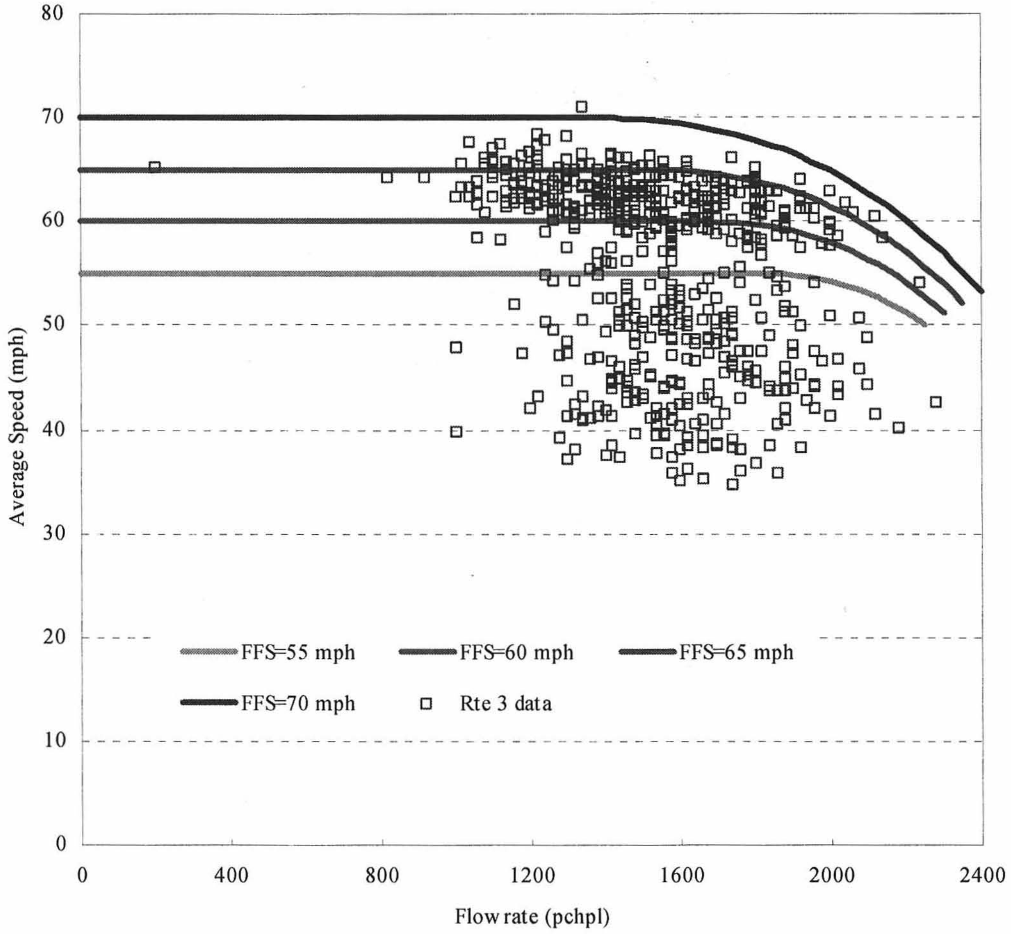

Figure A.11 Speed-Flow Models in HCM 2000 and Rte 3 Data

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