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Traffic Flow Characteristic and Capacity in Intelligent Work Zones

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DISCLAIMER

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TECHNICAL SUMMARY

NEXTRANS Project No 009IY01 Final Report, October 2009

Traffic Flow Characteristic and Capacity in Intelligent Work Zones

Introduction

Intellgent transportation system (ITS) technologies are utilized to manage traffic flow and safety in highway work zones. Traffic management plans for work zones require queuing analyses to determine the anticipated traffic backups, but the predictions are often inaccurate mainly because of lack of understanding of traffic flow characteristics in WZ. The current procedures for determining speed and capacity are inadequate and don't consider the fundamental effects of ITS technologies in traffic flow and drivers behavior. This study will address of traffic flow characteristics in Intelligent WZ and will determine methods for computing work zone capacity. Accurate determination of work zone capcity is very important because it significantly affects the speed and user's cost computations. Various ITS applications are implemented in the US (such as speed photo enforcement (SPE), dynamic lane management, variable speed control, travel time information display, dynamic rerouting, etc), but a major study to determine how traffic flow characteristics are affected in these intelligent WZ has not been conducted. This study investigated the fundamental relationship among traffic flow variables in a WZ where ITS was implemented for mainly as a speed control measure. A theoretical relationship was developed using field data collected in work zones.

Findings

The operating speed in an intelligent work zone is primarily influenced by the lane width, lateral clearance, work intensity and the type of ITS utilized in the work zone. Using SPE led to significant reductions in mean speed of vehicles and the magnitude of reduction depended on the free flow speed of vehicles. The reduction induced by SPE is linearly related to the free flow speed of vehicles before the SPE van becomes visible to them. For instance, for a free flow speed of 50 mph, the mean speed reduction is estimated as 4.5 mph whereas the mean speed reduction is anticipated as 8.4 mph when vehicles travel at a free flow speed of 65 mph.

In order to determine the operating capacity in the intelligent work zone where SPE was deployed, the fundamental speed-flow curve for the intelligent work zone is established and compared with the speed-flow curve for the same work zone when neither SPE nor another type of ITS was deployed as a speed control measure. The use of ITS in the work zone altered the relationship between space mean speed and traffic flow rate by lowering the speeds in the upper (uncongested) part of the speed-flow curve. The use of SPE also brought about a slight reduction of around 100 pcphpl in the maximum per-lane capacity of the two-lane-open work zone compared to when no SPE is utilized. With the speed-flow curve for the intelligent work zone established, one can use the operating speed as an input to accurately estimate the capacity of the intelligent work zone under the prevailing conditions. Accurate estimation of operating capacity of intelligent work zones gives rise to more effective operation on a real-time basis, more accurate diversion and traveler information for alternate routing and enhanced system reliability. Besides, it brings about improved knowledge on the characteristics of traffic flow in intelligent work zones.

Recommendations

The effects of other types of ITS on work zone operating speed and operating capacity have not yet been investigated. Therefore, it is recommended as future research that the outcomes of implementing other types of ITS such as changeable message signs, variable speed limits and dynamic late merge in highway work zones be investigated in order to gain a wider understanding of the traffic flow characteristics in intelligent work zones. It is also recommended to study the speed-flow relationship for work zone where congestion and queue is prevalent.

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CHAPTER 1. INTRODUCTION AND PROBLEM DEFINITION

1.1. Background and Motivation

Highway work zones continue to be a safety concern in the US. In 2007, motor vehicle crashes in U.S. work zones led to 835 fatalities and 105 fatal occupational injuries (National Work Zone Safety Information Clearinghouse, 2008). That the average annual number of fatalities was 698 between the years 1987 and 1997 illustrates the recent significant increase in the number of fatalities in U.S. work zones (FARS, 2005). In terms of billion dollars spent, the annual rate of work zone fatalities equals at least four times the annual fatality rate for total construction in the US (Mohan and Gautam, 2002). Thus, the crash data for U.S. highway work zones already indicate alarming rates.

Not only traffic safety but also maintenance-induced congestion is a serious concern in U.S. work zones. Since lower speed limits are posted in work zones, they bring about reductions in the capacity of the roadway. According to the recent studies, non-recurring conditions such as inclement weather, traffic incidents and special events account for approximately 50 percent of all highway congestion in the US. Currently, around 24 percent of non-recurring delay results from work zones on freeways (U.S. Department of Energy, 2002). Moreover, it is estimated that 60 million vehicles per hour per day of capacity was lost on account of work zones over a two week period when the summer roadwork season was in its peak in 2001 (U.S. Department of Transportation, 2002).

The use of Intelligent Transportation Systems (ITS) in work zones can be beneficial in both eliminating most safety problems and improving work zone capacity. According to Garber and Zhao (2002), rear-end collisions are the most predominant type of crashes in work zones, accounting for 83 percent of the total crashes in the advance warning areas of the highway work zones in Virginia. Salem et al (2006) and Garber and Zhao (2002) state that the predominance of rear-end collisions in highway work zones is attributed to high speed variation among vehicles and excessive vehicle speeds. Hence, the implementation of ITS in highway work zones is primarily aimed at preventing the speeding of drivers and reducing the speed variation. In this research, an intelligent work zone refers to a highway work zone where ITS is deployed as a speed control measure. Past studies show that the use of ITS in work zones has most of the times direct influence on vehicle speed distributions. Yet the influence of ITS on work zone capacity has not been investigated because work zone safety has remained to be the main concern. However, ITS-induced improvement in work zone capacity not only can reduce vehicle queues but also can decrease the potential of rear-end collisions. Therefore, it is progressively getting more common to implement ITS as a speed control measure in freeway work zones in addition to the traditional MUTCD signing.

1.2. Study Objectives

Since the effect of ITS on work zone capacity still remains unexplored, the speed-flow relationship in intelligent work zones is also undefined. Thus, the objective of this study is to investigate and find out the speed-flow relationship for intelligent freeway work zones. If the speed-flow relationship for intelligent work zones is established, the capacity of intelligent work zones can be accurately estimated. Accurate estimation of capacity of intelligent work zones provides more efficient operation in a real-time system, more appropriate information on travel pattern, more accurate diversion and traveler information for alternate routing and improved reliability of the system. Besides, establishing the speed-flow relationship will lead to better understanding of the traffic flow characteristics in intelligent work zones and will confirm whether the use of ITS in work zones alters the relationship between traffic flow parameters.

1.3. Organization of the Research

The remainder of the report is structured as follows: Chapter 2 addresses some approaches based on the former studies in the literature for investigating the traffic flow characteristics of freeway work zones and identifies the selected approach for this study. Chapter 3 gives detailed explanation about the application of the selected approach to intelligent work zones. In Chapter 4, the findings from the field data obtained from an intelligent work zone on I55 are presented. Besides, the findings from the intelligent work zone are compared with the findings from the same work zone when no ITS was deployed. In Chapter 5, the results of the research are summarized and recommendations for future research are provided.

CHAPTER 2. APPROACHES IN THE LITERATURE

This chapter addresses various approaches from the literature for investigating the traffic flow characteristics of freeway work zones. Section 2.1 presents two different approaches for estimating the operating speed in freeway work zones, based on some relevant studies in the literature. Section 2.2 includes two different approaches for estimating the operating capacity in freeway work zones, derived from some former studies. In Section 2.3, the selected approach for estimating the operating speed and operating capacity in intelligent work zones is presented.

2.1. Estimating the Operating Speed in Freeway Work Zones

The speed at which vehicles pass through the work activity area after adjusting their speed with regard to the prevailing conditions such as work intensity, lane width, etc… is called the operating speed in a work zone. Upon entering an activity area, motorists adjust their speeds on account of less-than ideal geometric conditions, work zone activity, weather conditions, etc… Both approaches presented in this section for estimating the operating speed in work zones are all based on the principle that the operating factors in work zones such as lane width, work intensity, lateral clearance as well as ITS implemented induce motorists to reduce their speeds.

2.1.1. Approach 1:

Benekohal et al (2004) developed a step-by-step methodology to estimate the operating speed in freeway work zones. The following relationship was established for estimating the speed reductions upon entering a work zone activity area:

$$U_o = FFS - R_{WI} - R_{LW} - R_{LC} - R_o \qquad \textit{Equation 2-1}$$

where

U_o = Operating speed in the intelligent work zone (mph)

FFS = Free flow speed of vehicles which was assumed to be equal to posted speed limit + 5 mph.

R_{WI} = Speed reduction due to work intensity (mph), evaluated from Equation 2-3 or Equation 2-4,

R_{LW} = Speed reduction due to lane width (mph), obtained from HCM 2000, Exhibit 21-4, page 21-5.

R_{LC} = Speed reduction due to lateral clearance (mph), obtained from HCM 2000, Exhibit 23-5, page 23-6.

R_o = Speed reduction due to the other factors that may lead to further reductions in speed (mph)

The speed reduction factors due to lane width and lateral clearance were based on those suggested by HCM 2000. On the other hand, the speed reduction effect of work intensity was quantified in accordance with the type of the work zone; i.e. whether the work zone is short-term or long term. The speed reduction effects of work intensity was observed to be lower in long-term work zones since drivers get accustomed to the activity area (Dudek and Richards, 1981).

In order to quantify the effect of work intensity on vehicle speeds, Benekohal et al (2004) first defined a quantity called work intensity ratio (WI_r) as follows:

$$WI_r = \frac{w+e}{p} \qquad \textit{Equation 2-2}$$

where

WI_r = Work intensity ratio,

w = Number of workers ranging from 0 to a maximum of 10 in the active work area,

e = Amount of large construction equipment present in the active work area, ranging from 0 to a maximum of 5,

p = Distance between the active work area and open lane (ft), ranging from 1 to a maximum of 9.

Afterwards, the speed reduction due to work intensity in short-term work zones is quantified as follows:

$$R_{WI} = 11.918 + 2.6766 \ln(WI_r) \qquad \textit{Equation 2-3}$$

where
WI_r is evaluated from Equation 2-2.

Likewise, the speed reduction effect due to work intensity in long-term work zones is quantified as follows:

$$R_{WI} = 2.6625 + 1.2056 \ln(WI_r) \qquad \textit{Equation 2-4}$$

where
WI_r is evaluated from Equation 2-2.

Both empirical equations were developed from a survey conducted among 120 drivers at a rest area and then verified with field data. Furthermore, as for the speed reduction factor R_o, the default value is 0 unless there is information regarding the magnitude of speed reduction. When traffic flow breakdown occurs, this methodology cannot provide an accurate estimation of operating speed. So under traffic flow breakdown conditions, the magnitude of R_o can be taken as the difference between the estimated operating speed and the speed measured in the field. For instance, Chitturi et al (2008) applied this model to estimate the operating speed in a long-term work zone near Litchfield, Illinois, where traffic flow breakdown conditions were observed. Without including the factor R_o, the model estimated the operating speed as 49.8 mph, which was substantially different than the actual speed of 19.2 mph observed in the field. Hence, the magnitude of R_o was taken to be 30.57 mph to account for the otherwise-excluded effects of traffic flow breakdown.

Advantages of Approach 1

1- The proposed model is the expanded form of a formerly-developed methodology whose accuracy in estimating the operating speed in work zones was already validated through field data and verifications (Benekohal et al, 2004, Chitturi et al, 2008).
2- The computation procedure is quite straightforward and easy.

Disadvantages of Approach 1

1- In order to account for the speed-reducing effects of lane width and lateral clearance, the corresponding HCM 2000 values were used in the model, which slightly reduces the degree of accuracy in the model (Benekohal et al, 2004, Chitturi et al, 2008).
2- The method does not take into consideration the effects of weather conditions on operating speed.
3- In the design stage, design engineer may not be able to accurately estimate the exact number of workers or large construction equipment in the work zone. Hence, a proper estimation of speed reduction due to work activity in the work zone may not be achieved in the design stage.

2.1.2. Approach 2:

The second approach assumes that the major factors affecting operating speed in intelligent work zones are the ITS deployed in the work zone, weather conditions, presence of work activity and lane width. The following linear regression model is suggested to estimate the operating speed in a work zone under the prevailing conditions:

$$U_o = FFS - A*WI - B*WE - C*(12\text{-}LW)^2 - \Delta_{ITS} \qquad \textit{Equation 2-5}$$

where

FFS = Free flow speed of vehicles which was assumed to be equal to posted speed limit + 5 mph.

U_o: Operating speed in the intelligent work zone (mph), SL: Posted speed limit in the intelligent work zone (mph),

WI: Dummy variable for work activity in the intelligent work zone (WI=0 if there is no worker and construction equipment present in the work zone, otherwise WI=1),

WE: Dummy variable for weather conditions (WE=0 for clear weather and light rain, WE=1 for moderate rain or light snowfall, WE=2 for heavy showers, heavy snowfall or freezing rain),

LW= Lane width (ft),

Δ_{ITS}: Effect of ITS on operating speed (mph),

A: Regression constant for the work activity (mph),

B: Regression constant for the weather conditions (mph),

C: Regression constant for the lane width (mph/ ft).

In this approach, it is proposed that there is a linear relationship between the second power of the variable (LW – 12') and the resulting speed reduction in the work zone. According to the HCM 2000, the adjustment to free-flow speed for lane width on a basic freeway section is performed according to Table 2-1.

Table 2-1. Adjustment to free-flow speed for lane width on freeway (HCM 2000)

Lane width (ft)	Reduction in free-flow speed (mph)
≥ 12	0
11	1.9
10	6.6

It is shown in Figure 2-1 that when linear regression is carried out by plotting the suggested speed reduction values due to lane width versus the variable $(LW – 12')^2$, it displays strong linear relationship with a coefficient of variation equal to 0.9975. Hence, it is suggested that the variable $(LW – 12\ ft)^2$ be included in the proposed linear regression model to estimate the operating speed in work zones.

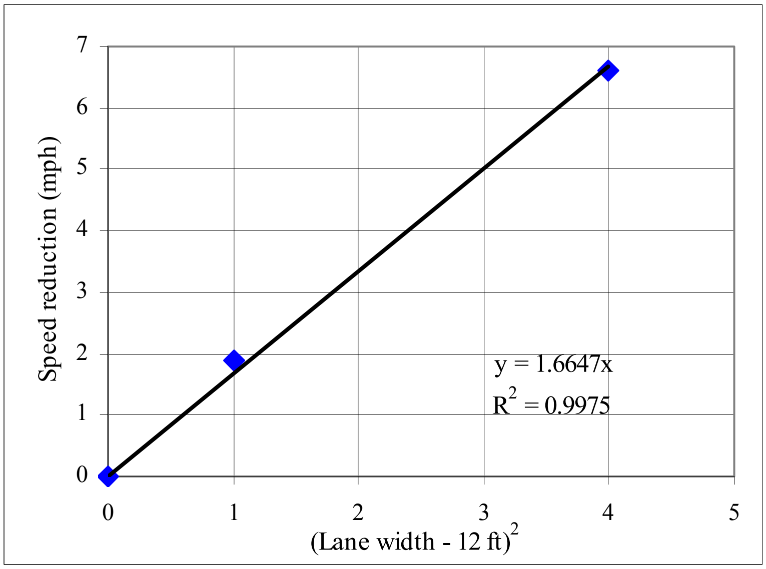

Figure 2-1. Relationship between the variable (Lane Width – 12')^2 and the speed reduction due to lane width as suggested by HCM 2000

Next, contrary to the approach developed by Benekohal et al (2004), the work activity is included as a dummy (binary) variable in this approach. In the design stage, design engineer may not be able to accurately estimate the exact number of workers or large construction equipment in the work zone, so the speed reduction factor due to work activity is incorporated as a binary variable to bring in further simplicity. Kim et al (2001) and Al-Kaisy and Hall (2003) also incorporated the work intensity as a binary dummy variable into their work zone capacity models. The accuracy of the model developed by Kim et al (2001) was validated through field evaluations.

Moreover, some past studies showed that inclement weather conditions significantly reduce free-flow speed of vehicles. Although no past study specifically and elaborately investigated the effect of inclement weather conditions on vehicle speeds in freeway work zones, the results of the most recent relevant study by Rakha et al (2008) are summarized in Table 2-2 to provide preliminary idea in respect of the effects of inclement weather conditions on vehicle speeds. Likewise, Table 2-3 gives the speed reduction ranges for inclement weather conditions suggested by HCM 2000.

Table 2-2. Speed reduction ranges owing to inclement weather conditions (Rakha et al, 2008)

Precipitation Intensity	Speed reduction range (%)
Light rain (0.01 cm/h)	2.0 – 3.6
Heavy rain (1.60 cm/h)	6.0 – 9.0
Light Snow (0.01 cm/h)	5.0 – 16.0

Table 2-3. Speed reduction ranges owing to inclement weather conditions (HCM, 2000)

Precipitation Intensity	Speed reduction range (%)
Light rain	1.9
Heavy rain	4.8 – 6.4
Light Snow	1.0
Heavy snow	35 – 40

Advantages of Approach 2

1- The determination of the operating speed in work zones does not involve HCM 2000 assumptions that can lead to reduced degree of accuracy as observed in the case of Chitturi et al (2008).

2- Unlike the approach developed by Benekohal et al (2004), the model takes into consideration the effects of weather conditions on operating speed in work zones.

3- The computation procedure is quite straightforward and easy.

Disadvantages of Approach 2

1.A linear regression model was formerly developed by Al-Kaisy and Hall (2003) and by Kim et al (2001) to estimate work zone capacity. The accuracy of the model was also verified by Kim et al (2001). However, the accuracy of such a linear regression model in estimating work zone operating speed was not previously validated.

2.2. Estimating the Operating Capacity in Work Zones

The capacity at which the work zone operates under the prevailing geometric, traffic control and work activity conditions is called the operating (service) capacity in the work zone. This section provides two different approaches for estimating the operating capacity in freeway work zones. The first approach requires the computation of the operating capacity from the operating speed in the work zone. On the other hand, the second approach necessitates that the operating capacity be computed by directly considering the effects of less-than ideal geometric conditions, work activity, inclement weather conditions and traffic control measures.

2.2.1. Approach 1:

The first approach is based on the work zone capacity estimation model by Benekohal et al (2004). Benekohal et al (2004) constructed speed-flow curves corresponding to different free-flow speeds in order to estimate the work zone operating capacity for a given operating speed. In order to develop the congested portion of the curve where the operating speed is lower than the optimal speed at maximum flow, the speed and flow in a work zone were computed for 5-minute time intervals and by considering only vehicles in platoon. After plotting the speed and flow values obtained from the field data, the following relationship was found to provide a good representation of the data points:

$$q = 145.68 * U_o^{0.6857} \qquad \textit{Equation 2-6}$$

where

q = Traffic flow in passenger cars per hour per lane (pcphpl)

U_o = Operating speed, which is lower than the optimal speed at maximum traffic flow.

It was assumed that no matter what the free-flow speed is, this relationship sets the congested part of the speed-flow curve in the work zone. On the other hand, the uncongested part of the speed-flow curve was constructed separately for each free-flow speed with regard to the information from the HCM 2000, the field data collected from the work zones and the knowledge of the authors. Assuming that free-flow speed begins to drop after a flow rate of 1,300 pcphpl, the following equation was established to form the relationship between the speed and flow rate provided that the magnitude of flow is between 1300 pcphpl and the corresponding maximum flow for the given free-flow speed:

$$U = FFS - \left(FFS - U_c\right) * \left[\frac{q - 1300}{C - 1300}\right]^{2.6}$$ *Equation 2-7*

where

U = speed (mph)

FFS = Free-flow speed (mph)

U_c = Optimal speed at maximum flow (mph)

q = Flow (pcphpl)

C = Capacity, i.e. the maximum flow rate which occurs at optimal speed (pcphpl)

Combining the congested and uncongested parts of the speed-flow curves, Benekohal obtained the speed-flow curves shown in Figure 2-2.

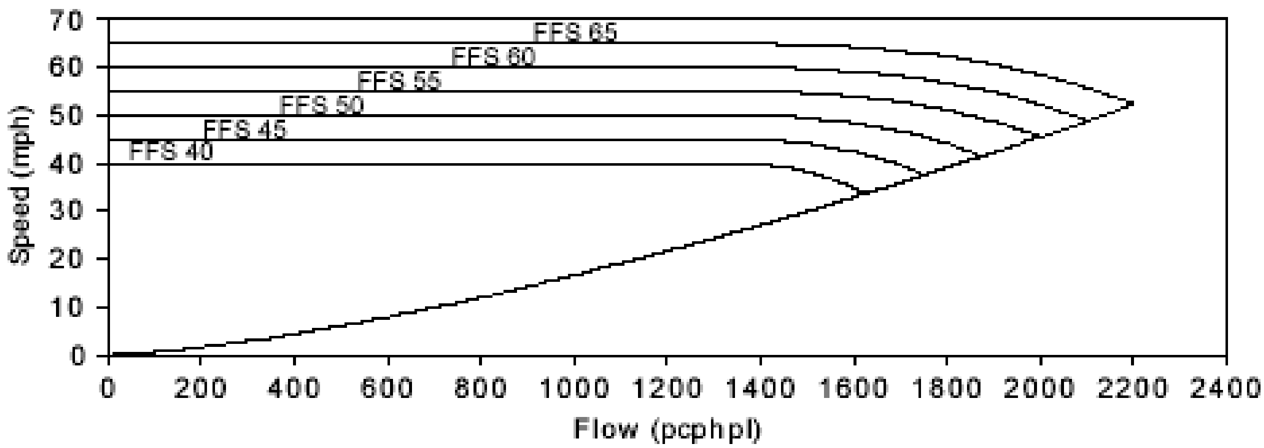

Figure 2-2. Speed-flow curves for work zones
(Benekohal et al, 2004)

Since the speed-flow curves for work zones are determined, the operating capacity at a computed operating speed can be found from Figure 2-2 by using the appropriate speed-flow curve with respect to the free-flow speed. The model was validated with field data and was found to give practically accurate estimates of work zone capacity (Benekohal et al, 2004; Chitturi et al, 2008).

Finally, after the traffic flow in pcphpl is determined from the operating speed, the flow rate should be expressed in vehicles per hour per lane (vphpl) by using the following relationship (Benekohal et al, 2004):

$$C_{adj} = C_{U_o} * f_{HV} * PF \qquad \textit{Equation 2-8}$$

where

C_{adj} : Adjusted capacity in vphpl,

C_{U_o} : Capacity at operating speed U_o in pcphpl,

f_{HV} : Heavy-vehicle adjustment factor, same as the one in HCM 2000,

PF : Platooning factor (default value is 1.0 unless otherwise is stated).

Advantages of Approach 1:

1- The accuracy of the approach in estimating the operating capacity in work zones was already validated through field data and verifications (Benekohal et al, 2004; Chitturi et al, 2008).

2- The methodology establishes a coherent and lucid relationship between the space mean speed and the flow rate by setting the speed-flow curves for each free-flow speed which in addition enhances the knowledge of capacity in work zones.

3- The method eliminates the adverse effect of large headways by removing them from the field data and in turn provides a more accurate approach.

Disadvantages of Approach 1:

1- The model does not take into account the effect of the number of opened and closed lanes. Sarasua et al (2006) showed that the per-lane capacity of a work zone is influenced by the number of closed and open lanes. Furthermore, factors like weather conditions and driver population are not considered in the model. For instance, Ahmed et al (2000) found that inclement weather conditions can reduce work zone capacity by up to 19 percent.

2- For every free-flow speed, the model assumes one common speed-flow curve representing congested traffic conditions.

2.2.2. Approach 2:

The second approach differs from the former in that it is founded on a linear regression model to determine the operating capacity under the prevailing conditions in work zones. The suggested linear regression model is anchored in the work zone capacity models developed by Kim et al (2001) and Al-Kaisy and Hall (2003). A major change incorporated into the model is that while the model of Kim et al (2001) involved the number of closed lanes as a regression variable, the suggested model uses the proportion of the number of closed lanes to the number of open lanes as a regression variable. Sarasua et al (2006) observed different per-lane capacity values for two-to-one lane closures, three-to-one lane closures and three-to-two lane closures in work zones. So it would be more definitive to include the ratio of the number of closed lanes to the number of open lanes in the model other than just the number of closed lanes itself. Another change made on the model of Kim et al (2001) was that the regression term representing the percentage of heavy vehicles was eliminated on the grounds that Kim et al (2001) found a relatively low correlation between the percentage of heavy vehicles itself and work zone capacity. Likewise, the regression term standing for the effect of lateral clearance on operating capacity is also removed because of the relatively low correlation observed by Kim et al (2001). The linear regression capacity model of Al-Kaisy and Hall (2003) did not involve a term in order to account for the effect of lateral clearance, either, and nevertheless, the results obtained from their model compared well with the actual capacity values observed in the field. Similarly, Adeli and Jiang (2003) did not take into consideration the effect of lateral clearance in their capacity estimation model, which resulted in average precision within 5.8 percent. Therefore, it is assumed that the omission of the lateral clearance term in the capacity estimation model will not bring about significant reductions in the degree of accuracy of the model. Besides, approach 2 also accounts for the effects of work zone length on operating capacity. According to Cassidy and Han (1993), work zone capacity decreases with increasing length of the work zone since it takes longer to process vehicles entering the work zone.

Moreover, two model involves two additional regression variables to account for the effects of weather conditions and the ITS deployed in the work zone. Hence, the following linear regression equation is suggested to estimate the operating capacity in intelligent work zones:

$$C_o = C_b - a*COR - b*WI - c*WE - d*(12-LW) - e*WG*HV - f*WL \pm C_{ITS} \qquad \textit{Equation 2-9}$$

where

C_o: Operating capacity in work zone (vphpl)

C_b: Base capacity in work zone (vphpl)

COR: Ratio of the number of closed lanes to the number of open lanes in one direction (unitless)

WI: Dummy variable for work intensity in work zone (WI=0 if there is no worker and construction equipment present in the work zone, otherwise WI=1),
WE: Dummy variable for weather conditions (WE=0 for clear weather conditions, WE=1 for Moderate rain or snowfall, WE=2 for heavy showers, heavy snowfall or freezing rain),
LW= Lane width (ft)
HV: Percent heavy vehicles in the traffic stream (unitless)
WG: Percent work zone grade
WL: Work zone length (ft)
C_{ITS}: Effect of ITS on operating capacity (vphpl)
a: Regression constant for the ratio of the number of closed lanes to the number of open lanes in one direction (vphpl),
b: Regression constant for the work intensity (vphpl),
c: Regression constant for the weather conditions (vphpl),
d: Regression constant for the lane width (vphpl/ ft),
e: Regression constant for the interactive effect of percent heavy vehicles and work zone grade (vphpl).
f: Regression constant for work zone length (vphpl/ft)

Past studies showed that the implementation of ITS in work zones can either reduce or increase the work zone throughput (Kang et al, 2006; Kang et al, 2004). That's why, the C_{ITS} term in Equation 2-9 can indicate either an increase or a reduction in work zone operating capacity. Relevant results of the past studies on work zone capacity are summarized in Table 2-4.

Table 2-4. Observed effects of various speed control techniques on work zone throughput (Kang et al, 2006; Kang et al, 2004)

Speed Control Technique	Range of Increase in Work Zone Throughput (vphpl)
Dynamic late merge	94 – 142

Speed photo enforcement	No data
Changeable message signs	No data
Changeable message signs with radar	No data
Speed monitoring display	No data

Furthermore, Ahmed et al (2000) observed that average capacity may be reduced by as high as 19 percent under shower, wet snow or freezing rain conditions compared to clear weather conditions. Table 2-5 shows the ranges of capacity reduction suggested by Rakha et al (2008) owing to inclement weather conditions. It is to be noted that there exists no past study which specifically and elaborately investigated the effects of inclement weather conditions on work zone operating capacity.

Table 2-5. Capacity reduction ranges owing to inclement weather conditions (Rakha et al, 2008)

Precipitation Intensity	Capacity reduction range (%)
Light rain (0.01 cm/h)	10-11
Heavy rain (1.60 cm/h)	10-11
Light Snow	12-20
Heavy Snow	35-40

Advantages of Approach 2:

1. The determination of the effects of heavy vehicles on work zone capacity does not resort to the relevant assumptions in HCM 2000.
2. Unlike the model developed by Benekohal et al (2004), the model takes into consideration the effects of weather conditions and work zone length on operating capacity.
3. The methodology entails a linear regression model for estimating operating capacity in work zones. Since the linear regression model does not involve the estimated operating speed as an input variable, possible errors made in estimating the

operating speed in work zone will not be introduced into the operating capacity estimation model. In other words, the stage of estimating the operating capacity will be completely independent from the stage of estimating the operating speed.

4. A similar linear regression model was already developed by Kim et al (2001) and Al-Kaisy and Hall (2003). Kim et al (2001) compared the accuracy of their model with that of other capacity models including that of HCM 2000 model. The model by Kim et al (2001) brought about average precision within 8.2 percent, which is superior to the degree of precision the model by Benekohal et al (2004) provided (Chitturi, 2008).
5. The computation procedure is quite straightforward and easy.

Disadvantages of Approach 2:

1. The major shortcoming of the model is that it does not construct a speed-flow curve to clearly indicate the relationship between speed and flow in the work zone.
2. The development of the model requires data collection for determining the effects of the factors included in the linear regression model on operating capacity.
3. The method does not involve a platooning factor to eliminate the adverse effect of large headways in traffic stream.

2.3. Selected Approach

Considering the advantages and disadvantages of both approaches for estimating the operating speed in freeway work zones, approach 1 by Benekohal et al (2004) defined in Section 2.1.1 is selected. Although approach 2 defined in Section 2.1.2 also offers remarkable advantages, approach 1 is chosen owing to the fact that it explicitly assigns an estimated speed reduction value to each speed-reducing factor, providing a better understanding of the speed characterstics in work zones. Therefore, it is suggested that approach 1 defined in Section 2.1.1 be improved and utilized for estimating the operating speed in intelligent work zones.

Next, as far as the advantages and disadvantages of each approach for estimating the capacity in freeway work zones are considered, approach 1 by Benekohal et al (2004) defined in Section 2.2.1 is selected. Despite the notable advantages offered by approach 2 defined in Section 2.2.2, approach 1 is chosen on the grounds that it sets the speed-flow curve for each free-flow speed and thereby, it provides a clear illustration of the relationship between the space mean speed and the traffic flow rate. Consequently, it is proposed that approach 1 defined in Section 2.2.1 be improved and employed to estimate the operating capacity in intelligent work zones.

CHAPTER 3. METHODOLOGY

In this chapter, the application of the selected approaches to the determination of traffic flow characteristics in intelligent work zones is discussed. Section 3.1 provides an improved methodology for estimating the operating speed in intelligent work zones based on the relevant approach of Benekohal et al (2004). In Section 3.2, an improved methodology for estimating the operating capacity in intelligent work zones is presented.

3.1. Methodology for Estimating the Operating Speed in Intelligent Work Zones

It is suggested that approach 1 defined in Section 2.1.1 be improved for estimating the operating speed in intelligent work zones because it was originally not intended for intelligent work zones. Therefore, it does not take into consideration the speed-reducing effects of ITS deployed in intelligent work zones. Several studies in the literature showed that the implementation of various ITS gave rise to significant speed reductions in intelligent work zones (Benekohal et al., 2008; Zech et al, 2008; Garber and Srinivasan, 1998; Garber and Patel, 1995; McCoy et al, 1995; Pesti and McCoy, 2001; Brewer et al, 2006). Therefore, an additional speed reduction factor has to be incorporated into the operating-speed model to explicitly account for the effect of ITS on vehicle speeds.

Hence, the assessment of the effects of ITS on operating speed and traffic flow is incorporated into the model of Benekohal et al (2004). It is suggested that the additional speed reduction term be added to the model as follows:

$$U_o = FFS - R_{WI} - R_{LW} - R_{LC} - R_{ITS} - R_o \qquad \textit{Equation 3-1}$$

where

U_o = Operating speed in the work zone (mph)

FFS = Free flow speed of vehicles which was assumed to be equal to posted speed limit + 5 mph.

R_{WI} = Speed reduction due to work intensity (mph), evaluated from Equation 2-3 or Equation 2-4,

R_{LW} = Speed reduction due to lane width (mph), obtained from Table 3-1 (Chitturi and Benekohal, 2005),

R_{LC} = Speed reduction due to lateral clearance (mph), obtained from HCM 2000, Exhibit 23-5, page 23-6.

R_o = Speed reduction due to the other factors that may lead to further reductions in speed (mph)

R_{ITS} = Speed reduction due to the ITS deployed in the work zone, mph.

An improvement in Equation 3-1 is the modification of the speed reduction term due to lane width (R_{LW}). Chitturi and Benekohal (2005) found that the reductions in free flow speeds of vehicles in work zones are higher than those given in the Highway Capacity Model for basic freeway sections. According to the results of their study, the speed reduction values shown in Table 3-1 were observed on account of less-than-ideal lane width in work zones. Therefore, it is suggested that the speed reduction term due to lane width (R_{LW}) in Equation 3-1 be based on the values in Table 3-1.

Table 3-1. Adjustment to free-flow speed for lane width on freeway work zones (Chitturi and Benekohal, 2005)

Lane width (ft)	Reduction in free-flow speed (mph)
12	0.0
11	4.4
10.5	7.2

Another improvement in Equation 3-1 is the incorporation of the speed reduction term due to the ITS (R_{ITS}). The term R_{ITS} accounts for the speed reduction effects of the ITS implemented in the intelligent work zone. Based on the results of relevant past studies, Table 3-2 gives the speed reduction range of various speed control strategies used in work zones (Benekohal, 1992; Mattox III et al, 2007; Benekohal et al, 2008). In view of the results from past studies, Table 3-2 also includes the preliminary suggested values for speed reduction factor due to ITS in Equation 3-1.

Table 3-2. Observed speed reduction range of various ITS in intelligent work zones

Speed Control Technique	Observed Range of Speed Reduction (mph)	Suggested Speed Reduction (mph)
Changeable Message Signs*	1.4 - 4.7	3.0
Changeable Message Signs with Radar**	4.0 - 8.0	5.0
Dynamic Late Merge	No Data	No Data
Speed Photo Enforcement***	3.4 - 7.8	5.0
Speed Monitoring Display**	4.0 - 5.0	4.0

* Benekohal, 1992, **Mattox III et al, 2007, *** Benekohal et al, 2008

However, the range of the results presented in Table 3-2 is wide and speed reductions are not correlated to different speed levels the traffic may have had. In order to precisely evaluate the speed reduction effects of a particular type of ITS, field data should be collected in an intelligent work zone deploying the ITS and then the data should be compared with base data collected under similar conditions except the implementation of the ITS.

In order to investigate the speed-reducing effects of Speed Photo Enforcement (SPE), three data sets were collected in two work zones on Interstate Highways (Benekohal et al, 2008). The first data set was collected during the AM off-peak period on I-64EB (MP=14) in southern Illinois near St Louis. The second data set was collected during the PM off-peak period in the same work zone as the first data set was collected. The work zone on I-64 EB involved the addition of a third lane in the median. It had two lanes open to through traffic and concrete barriers were used to separate the activity area from the open lanes. The posted speed limit in the work zone was 55 mph. On the other hand, the third data set was collected during the off-peak hours in the afternoon in a work zone on I-55NB (MP=259) near Chicago. It had also two lanes open to through traffic and the posted speed limit was 55 mph. The work zone on I-55NB (MP=259) was for lane addition and bridge deck repair.

In all the data sets, traffic flow data were collected for three different scenarios:

1. Base Data: The work zone did not involve any speed enforcement other than the standard MUTCD signing.
2. Speed Photo Enforcement (SPE) Data: An SPE van was implemented in the work zone as a speed control measure.

The traffic flow parameters obtained from the base data set enables the comparison of them with the traffic flow parameters under the implementation of the SPE in the work zone. The location where traffic flow data were collected was several hundred feet downstream of the SPE van, which enabled motorists to react to the SPE. All the other factors that influence the operating speed in the work zone such as weather conditions, work intensity, lane width, etc… were the same in both cases. Therefore, the average speed differences between the base case and SPE case are attributed to the implementation of SPE in the work zone. The results are presented in Chapter 4, Section 4.1.

3.2. Methodology for Estimating the Operating Capacity in Intelligent Work Zones

It is suggested that approach 1 defined in Section 2.2.1 be improved for estimating the operating speed in intelligent work zones since the implementation of ITS in work zones may lead to a different relationship between work intensity and the consequent speed reduction. Thus, the speed-flow curves for work zones developed by Benekohal et al (2004) require further modification in order to reflect the traffic flow characteristics in intelligent work zones. Yulong and Leilei (2007), Kang et al (2006) and Kang et al (2004) observed that the use of intelligent merge control systems and variable speed limits increased the throughput in work zones. Likewise, Kwon et al (2007) found out that the use of variable speed limits in work zones can increase work zone throughput as high as 20 percent. Therefore, the use of ITS in a work zone is expected to lead to a different speed-flow curve compared to that of a work zone that does not deploy ITS. Hence, field data should be collected in intelligent work zones in order to set the appropriate relationship between operating speed and flow rate.

In order to establish the relationship between the operating speed and capacity of work zones where SPE is employed and data was collected in a work zone on I-55. The data collected on June, 20, 2007, from 2 pm to 3 pm when no ITS was utilized is called "Base" case. The speed limit in the work zone was 55 mph. Another data set was collected on July 11, 2007, from 2 pm to 3 pm when SPE was implemented in the work zone; this is referred to as the "SPE" case. Since all the other factors that influence the capacity in the work zone such as weather conditions, work intensity, lane width, etc… were the same in both cases, any difference in work zone capacity between the two cases can be attributed to the implementation of SPE in the work zone. The results are presented in Chapter 4, Section 4.2.

CHAPTER 4. FINDINGS

Chapter 4 presents the results obtained from the aforementioned field data from the intelligent work zones where SPE was deployed as a speed control measure. In Section 4.1, the speed reduction effects of SPE are analyzed and indicated. In Section 4.2, the relationship between space mean speed and flow rate is presented for the intelligent work zone where SPE was deployed. Besides, the fundamental speed-flow curve obtained from the intelligent work zone with SPE is compared with that obtained from the same work zone when only standard MUTCD signing was used. Moreover, Section 4.3 provides the validation of the speed-flow models established in Section 4.2.

4.1. Determining the Speed Reduction Effects for Speed Photo Enforcement (SPE)

In order to establish the relationship between the speed reductions induced by the SPE, the average speeds obtained from the Base data are compared with the average speeds obtained from the SPE data. In order to eliminate the effects of platooning, only free flowing passenger cars were considered. Free flowing vehicles were defined as those vehicles which have a headway, not less than 4 second and a spacing, not less than 250 feet.

First, the overall average speed of the free-flowing passenger cars was computed for each Base data set. Next, each SPE data set was divided into 10-minute intervals such that the average speed of the free-flowing passenger cars was calculated for each 10-minute interval. Following this, each 10-minute average speed of a particular SPE data set was compared with the overall average speed of the corresponding Base data set. Each 10-minute average speed of the SPE data set was subtracted from the overall average speed of the corresponding Base data set. Thereby, depending on the total length of each SPE data set, up to six different speed reduction values were computed. The results are tabulated in Table 4-1. For instance, Table 4-1 shows that the overall average speed of the free-flowing vehicles in base data set 1 is 57.0 mph. On the other hand, the SPE data set 1 has a total duration of 60 minutes, so it was divided into six 10-minute intervals and the average speed of the free-flowing vehicles in each 10-minute interval was evaluated. The average speed of the free-flowing vehicles in the first 10-minute interval is 49.2 mph, and the average speed of the free-flowing vehicles in the sixth 10-minute interval is 51.9 mph. The first speed reduction value for data set 1 is calculated by subtracting 49.2 mph from 57.0 mph and is found as 7.8 mph. The sixth speed reduction value for data set 1 is computed by subtracting 51.9 mph from 57.0 mph and is found as 5.1 mph.

Table 4-1. Speed reduction effects of SPE on passenger cars (Benekohal et al, 2008)

<table>
<tr><th rowspan="2"></th><th colspan="3">Median Lane</th><th colspan="3">Shoulder Lane</th></tr>
<tr><th>Base Free Flow Speed (mph)</th><th>SPE Free Flow Speed (mph)</th><th>Speed Reduction by SPE (mph)</th><th>Base Free Flow Speed (mph)</th><th>SPE Free Flow Speed (mph)</th><th>Speed Reduction by SPE (mph)</th></tr>
<tr><td rowspan="6">Data set 1</td><td rowspan="6">57.0</td><td>49.2</td><td>7.8</td><td rowspan="6">51.2</td><td>46.9</td><td>4.3</td></tr>
<tr><td>50.4</td><td>6.6</td><td>47.8</td><td>3.4</td></tr>
<tr><td>50.0</td><td>7.0</td><td>47.3</td><td>3.9</td></tr>
<tr><td>51.7</td><td>5.3</td><td>46.9</td><td>4.3</td></tr>
<tr><td>50.6</td><td>6.4</td><td>46.6</td><td>4.6</td></tr>
<tr><td>51.9</td><td>5.1</td><td>46.2</td><td>5.0</td></tr>
<tr><td rowspan="3">Data set 2</td><td rowspan="3">55.4</td><td>49.5</td><td>5.9</td><td rowspan="3">50.2</td><td>46.4</td><td>3.8</td></tr>
<tr><td>47.7</td><td>7.7</td><td>43.7</td><td>6.5</td></tr>
<tr><td>50.0</td><td>5.4</td><td>44.2</td><td>6.0</td></tr>
<tr><td rowspan="6">Data set 3</td><td rowspan="6">63.7</td><td>56.9</td><td>6.8</td><td rowspan="6">61.5</td><td>54.7</td><td>6.8</td></tr>
<tr><td>55.9</td><td>7.8</td><td>52.9</td><td>8.6</td></tr>
<tr><td>56.8</td><td>6.9</td><td>53.2</td><td>8.3</td></tr>
<tr><td>55.3</td><td>8.4</td><td>53.2</td><td>8.3</td></tr>
<tr><td>57.8</td><td>5.9</td><td>54.4</td><td>7.1</td></tr>
<tr><td>52.6</td><td>11.1</td><td>53.6</td><td>7.9</td></tr>
</table>

Figure 4-1 illustrates the observed speed reductions versus the measured free flow speeds for the passenger cars. Figure 4-2 confirms that there is a linear relationship between the measured free flow speeds in the base data sets and the corresponding speed reductions induced by the SPE van. Hence, when SPE is used as a speed control measure in the intelligent work zone, there is no single value that can be assigned to the speed reduction term in Equation 3-1, R_{ITS}. Indeed, the magnitude of the speed reduction term in Equation 3-1, R_{ITS}, depends on the free flow speed of the passenger cars before the SPE van is visible to the motorists.

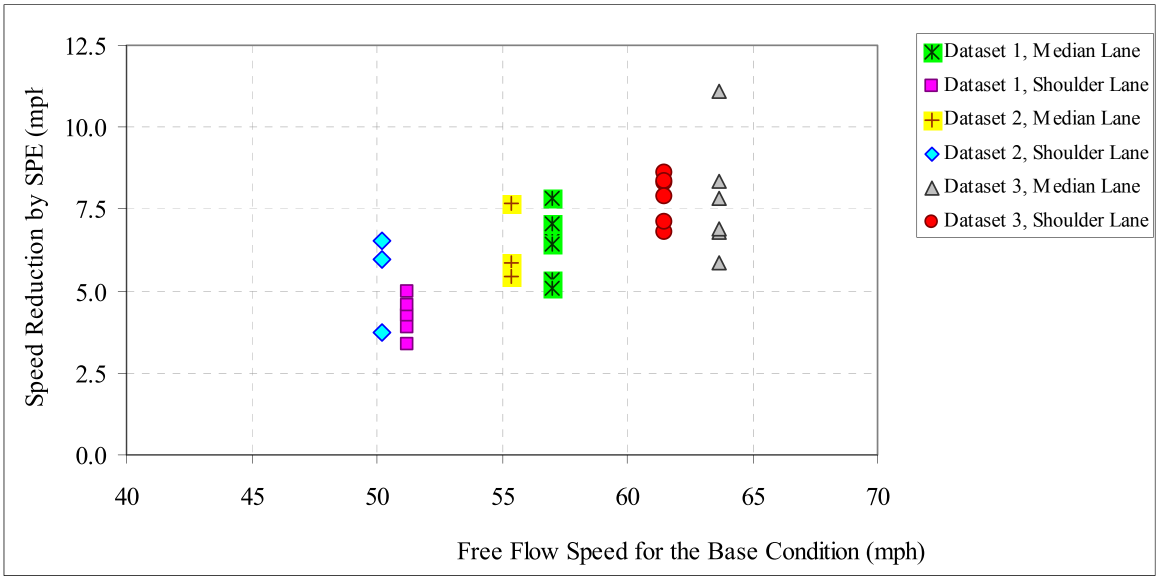

Figure 4-1. The mean speed of passenger cars in the base data set plotted versus the observed speed reductions induced by SPE

(Benekohal et al, 2008)

The linear trend indicated in Figure 4-2 shows that when SPE is deployed in an intelligent work zone, the speed reduction due to the SPE can be estimated from the following linear relationship for passenger cars:

$$R_{SPE} = 0.2598 * FFS_{PC} - 8.4443 \qquad \textit{Equation 4-1}$$

where

R_{SPE}: Speed reduction induced by SPE for passenger cars (mph), the R_{ITS} term in Equation 3-1 when SPE is deployed in the intelligent work zone,

FFS_{PC}: Free flow speed for passenger cars (mph) before the SPE van is visible to the motorists.

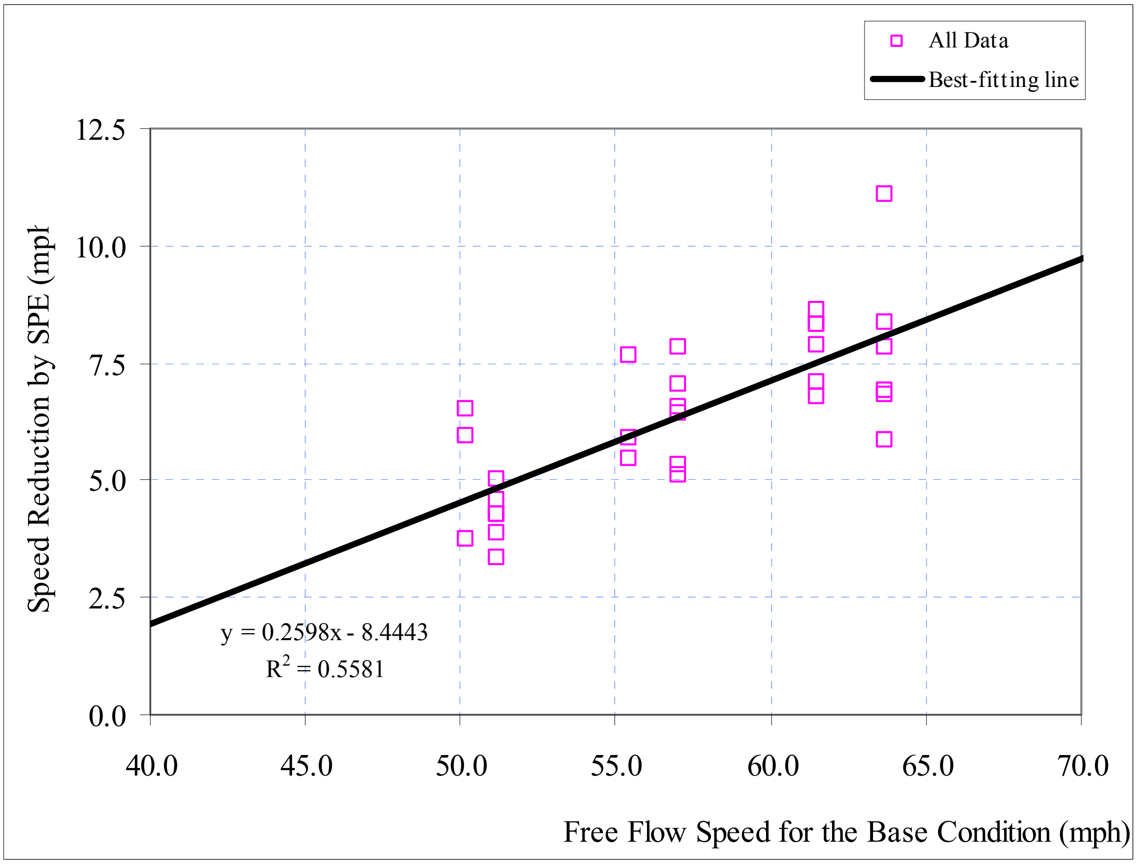

Figure 4-2. The estimated linear trend between the mean speed of passenger cars and the observed speed reduction induced by SPE (Benekohal et al, 2008)

Table 4-2 shows the estimated values of the speed reduction induced by speed photo enforcement for some free flow speeds. All the estimated speed reduction values are computed from Equation 4-1.

This study does not involve field data that can be used to estimate the speed reduction effects of other ITS in freeway work zones. Therefore, Table 3-2 can be used to estimate the speed reduction term, R_{ITS}, in Equation 3-1 when another type of ITS is utilized in an intelligent work zone.

Table 4-2. Estimated speed reduction values induced by speed photo enforcement for passenger cars

Free Flow Speed of passenger cars before SPE van is visible to the motorists (mph)	Estimated Speed Reduction by SPE (mph)
40.0	1.9
45.0	3.2
50.0	4.5
55.0	5.8
60.0	7.1
65.0	8.4

4.2. Developing Speed-Flow Relationships for Intelligent Work Zones

In this section, the Base and SPE data from I55NB (MP=259)are used to investigate the traffic flow characteristics in the intelligent work zone where SPE was deployed. Both the base and the SPE data sets consist of one-hour traffic flow data which include vehicle headways, vehicle speeds and vehicle type. Both data sets were aggregated separately by computing the space mean speed in mph and the corresponding flow rate in pcphpl at 2-minute intervals. The traffic data for the median lane and the shoulder lane were aggregated separately and then the data points obtained from the median lane and the shoulder lane are plotted together for each case. The data are shown in Figure 4-3. It should be noted that the PCE value of 1.5 was used to convert flow rate from vphpl to pcphpl. This PCE value is the one suggested by HCM 2000 for basic freeway sections on level terrain. Next, the two-minute flow rates of the Base data set are compared with those of the SPE data set using t-test (58 data points for each case). The results showed that the 2-minute traffic flow rates of the base data set are not significantly different from those of the SPE data set at 95-percent confidence level. Similarly, another unpaired t-test was applied to determine if the space mean speeds of the base data set are significantly different from those of the SPE data set. The results showed that the 2-minute space mean speeds of the base data set are significantly different from those of the SPE data set at 95-percent confidence level. Since volume and the other speed-reducing factors in the work zone such as weather conditions, work intensity and lane width were the same when both data sets were collected, the significant difference in space mean speeds is attributed to the implementation of SPE in the work zone.

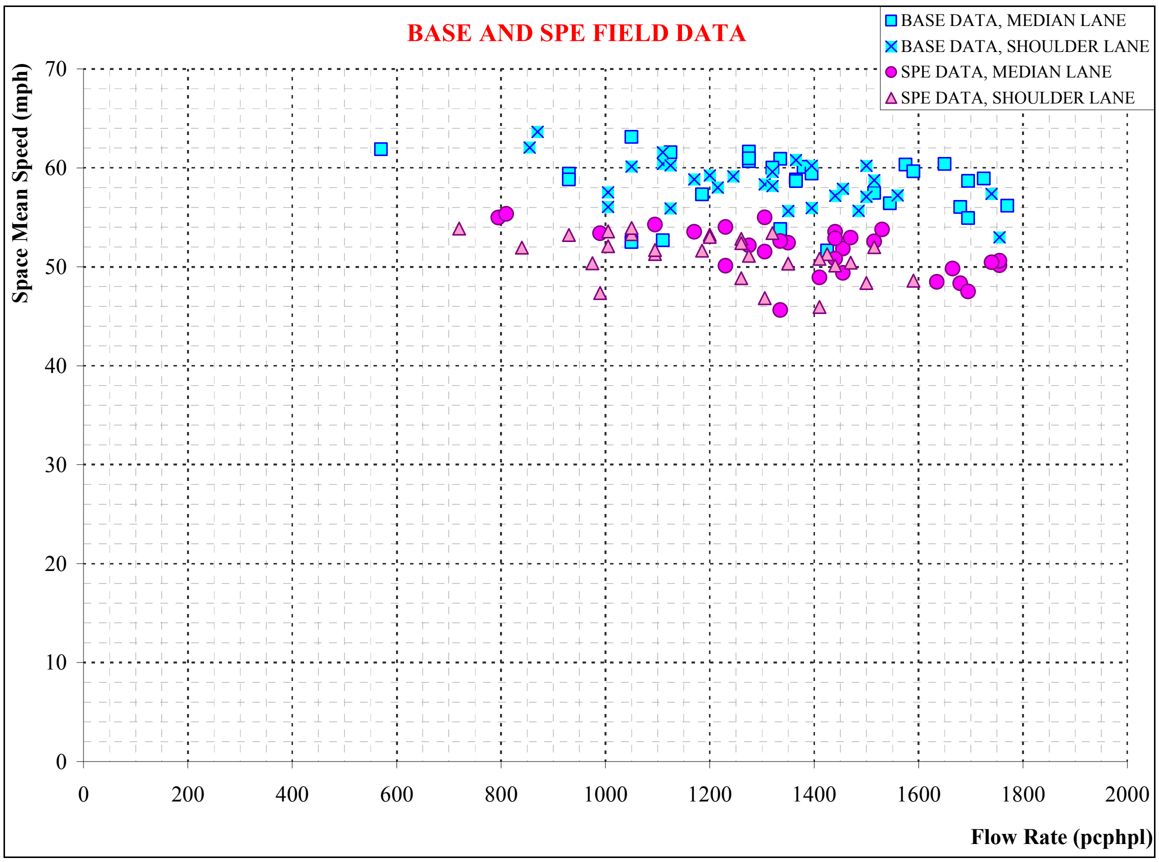

Figure 4-3. 2-minute aggregated field data obtained from the base and SPE data sets collected in a work zone on I55

Next, a mathematical model is fitted to each data set to represent the relationship between space mean speed and flow rate in the observed range. In this study, it was decided that for volumes of up to about 800 pcphpl, the speed will not change as flow increases. This value is less than the 1300 pcphpl that HCM uses for a basic freeway section with free flow speed of 70 mph. The 1300 is used when capacity of the basic freeway section is assumed to be 2400 pcphpl. However, work zones will have much lower capacity than the 2400. Thus, the bending point of the speed flow curve for work zones should be much less than the 1300 pcphpl. The 800 pcphpl seems a reasonable value to use, since there is not enough field data to determine the bending point of the speed-flow curve for work zones.

So a mathematical model in the form of Equation 4-3 is fitted to each data set:

$$U = FFS - (a * FFS - b) * \left(\frac{Q-800}{c-d*FFS}\right)^{e}$$

Equation 4-2

U: Operating speed of passenger cars (mph), $U > U_{optimum}$ where $U_{optimum}$ is the speed at which the maximum flow rate is observed,

Q: Flow rate (pcphpl), $800 \leq Q \leq Q_{peak}$,

FFS: Free flow speed of passenger cars,

a, b, c, d, and e: Regression constants.

It should be noted that in order to have a reasonable estimate of the exponent, this constant was set to be a value between 2.1 and 3.6 with an increment of 0.5. After examining the shape of the transition curves and their speed reductions, the exponent of 3.6 was found to be the most suitable one. Compared to the relevant speed-flow models in HCM 2000, **Error! Reference source not found.** has two major differences:

1. The power of the HCM 2000 models is 2.6 whereas the power of the model in **Error! Reference source not found.** is 3.6. Higher exponent means that the increase in flow rate brings about more rapid reduction in speed in work zones compared to in basic freeway sections.
2. The model in **Error! Reference source not found.** is based on the assumption that free flow takes place when the flow rate is less than 800 pcphpl. So when the flow rate is less than 800 pcphpl, the space mean speed is assumed to be equal to the free flow speed.

After the format of the mathematical model was set, nonlinear least squares estimation was carried out to determine the parameters of FFS, a, b, c and d in **Error! Reference source not found.**. The mathematical model in Equation 4-3 is found to represent the traffic flow conditions in the base data set:

$$U = FFS - (1.0 * FFS - 20.6) * \left(\frac{Q - 800}{2208 - 3.9 * FFS}\right)^{3.6} \qquad \textit{Equation 4-3}$$

where

U: Operating speed of passenger cars (mph), $U > U_{optimum}$ where $U_{optimum}$ is the speed at which the maximum flow rate is observed *(for $U_{optimum}$, please refer to page 37)*,

Q: Flow rate (pcphpl), $800 \leq Q \leq Q_{peak}$ *(for Q_{peak}, please refer to page 37)*,

FFS: Free flow speed of passenger cars (59.1 mph).

On the other hand, the mathematical model in Equation 4-4 is found to represent the traffic flow conditions in the SPE data set:

$$U = FFS - (1.1 * FFS - 15.9) * \left(\frac{Q - 800}{2143 - 4.9 * FFS}\right)^{3.6} \qquad \textit{Equation 4-4}$$

where

U: Operating speed of passenger cars (mph), $U > U_{optimum}$ where $U_{optimum}$ is the speed at which the maximum flow rate is observed *(for $U_{optimum}$, please refer to page 37)*,

Q: Flow rate (pcphpl), $800 \leq Q \leq Q_{peak}$ *(for Q_{peak}, please refer to page 37)*,

FFS: Free flow speed of passenger cars (52.1 mph).

Both the base model in Equation 4-3 and the SPE model in Equation 4-4 represent the traffic conditions in the work zone when no congestion or no flow break-down takes place. In both models, it is assumed that space mean speed is equal to the free flow speed when the flow rate is less than 800 pcphpl. Hence, the speed-flow curve takes the form of a straight line at free flow speed once the flow rate drops below 800 pcphpl. For the base data set, the free flow speed is found as 59.1 mph as shown in Equation 4-3 whereas it is found as 52.1 mph for the SPE data set as indicated in Equation 4-4. Both mathematical models are plotted in Figure 4-4.

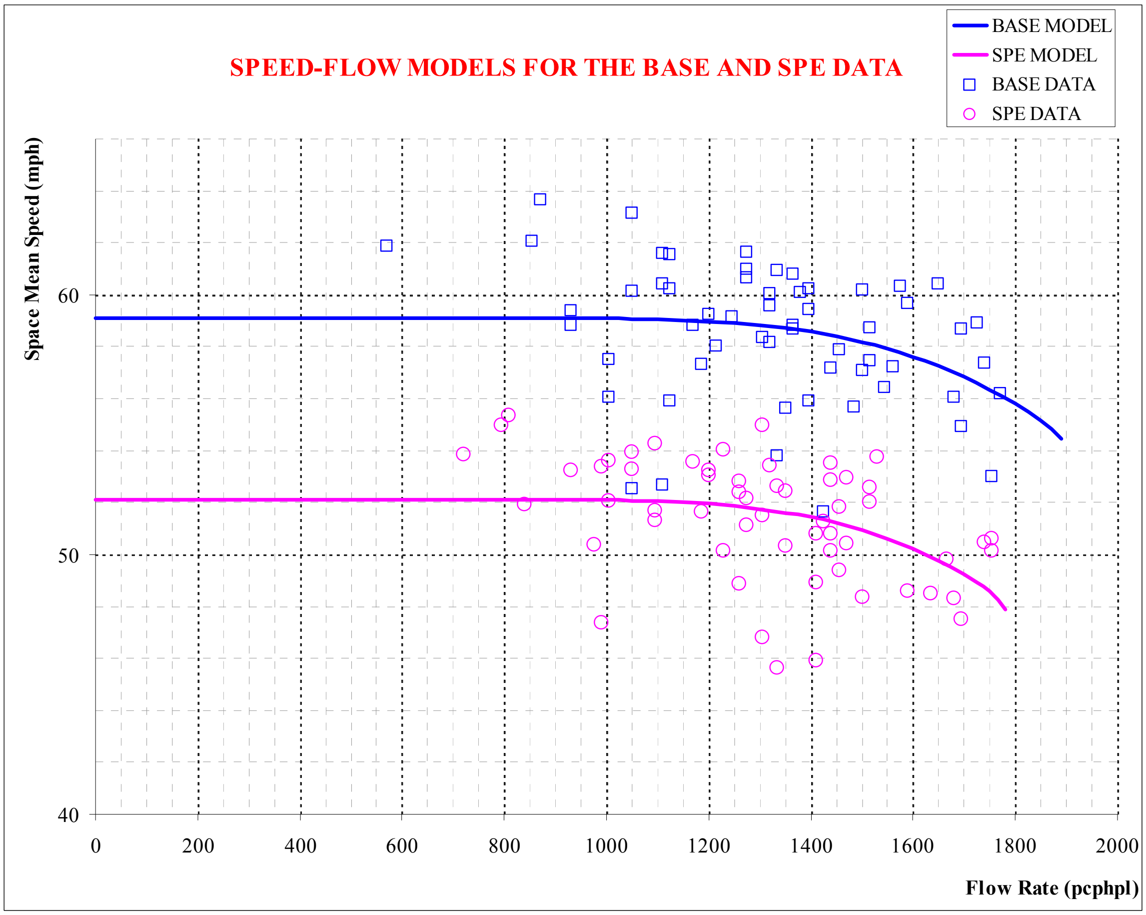

Figure 4-4. Mathematical models to represent the relationship between space mean speed and flow rate in the two-lane-open work zone on I55

Following this, the congested part of the speed-flow curve for each data set needed to be established. However, there was no congestion at the site under study, so appropriate field data from another site(s) is used to establish the congestion model. In order to set the congestion model, formerly-collected field data from one-lane-open work zones on I55NB (MP=55) and I74EB (MP=5) were used. The speed limit in both work zones was 55 mph which is the same as in the two-lane-open work zone on I55NB (MP=259) where the base and SPE field data were collected. Both I55NB (MP=55) and I55NB (MP=259) had ideal lane width and lateral clearance but I74EB (MP=5) had an 11 ft lane width which is less than ideal condition. A study by Benekohal et al. (2004) suggested 1.9 mph as speed reduction due to an 11 ft lane width. To account for the effects of the 11 foot lane and bring it to an equivalent of 12 ft lane, the speeds were adjusted upward by 1.9 mph, in the I74EB (MP=5) data.

The congestion data from the one-lane-open work zones on I55NB (MP=55) and I74EB (MP=5) was aggregated at 2-minute intervals such that the space mean speed and the corresponding flow rate for each 2-minute interval was computed. However, in order to properly represent the traffic congestion conditions and in order to eliminate long gaps in the traffic stream, only vehicles in platoon were considered in the data aggregation. A particular vehicle is considered to be in platoon if it was observed to maintain headway less than 4.0 seconds or if it was observed to maintain a front bumper-to-front bumper spacing less than 250 ft. Once the data aggregation was achieved, a power function in the form of Equation 4-5 was fitted to the data as follows:

$$Q = 271.43 * U^{0.4868} \qquad \textit{Equation 4-5}$$

where

Q: Flow rate (pcphpl),

U: Operating speed (mph),

After the congestion model was set, it was assumed that the model in Equation 4-5 represented the congested traffic conditions in the two-lane-open work zone on I55NB (MP=259) for both SPE and Base condition. Figure 4-5 illustrates the complete speed-flow curves obtained when the congestion model in Equation 4-5 is combined with the base model in Equation 4-3 and with the SPE model in Equation 4-4.

Considering the speed-flow curves shown in Figure 4-5 as well as Equation 4-3 and Equation 4-5, the capacity (maximum flow rate) of a single lane in the two-lane-open work zone on I55NB (MP=259) is computed as 1900 pcphpl when no ITS is deployed in the work zone. The maximum flow rate is reached at an optimum operating speed of 54.4

mph. So for the **base** case when no ITS is deployed in the work zone, $\mathbf{Q_{peak}}$ **= 1900 pcphpl** and $\mathbf{U_{optimum}}$ **= 54.4 mph**.

On the other hand, taking into account Figure 4-5 as well as Equation 4-4 and Equation 4-5, the capacity of a single lane of the two-lane-open work zone on I55 is computes as **1788 pcphpl** when **SPE** is implemented in the work zone. The maximum flow rate is reached at an optimum operating speed of 48.1 mph. Thus, when **SPE** is implemented in the work zone, $\mathbf{Q_{peak}}$ **= 1788 pcphpl** and $\mathbf{U_{optimum}}$ **= 48.1 mph**. In the meantime, since the aggregation of the traffic data from the two-lane-open work zone on I55 was achieved separately for the median lane and the shoulder lane, the capacity values read from Figure 4-5 does not mean that those maximum flow rates can be maintained on both lanes simultaneously.

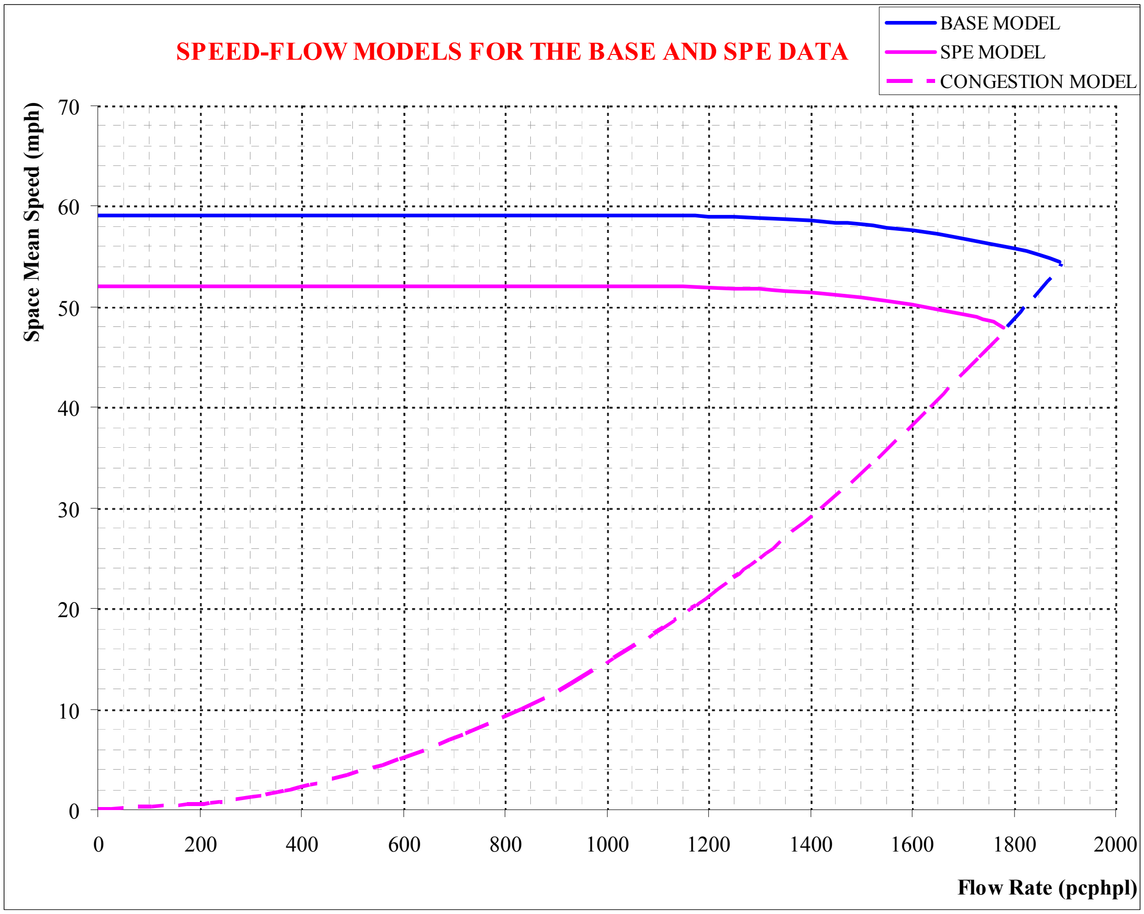

Figure 4-5. Complete speed-flow curves to represent the relationship between space mean speed and flow rate in the two-lane-open work zone on I55NB(MP=259)

4.3. Verifying Capacity Values

In order to verify the maximum flow rates obtained from the speed-flow curves in Figure 4-5, the field data were further analyzed. The maximum flow rates sustained for 15 minutes on the shoulder and median lanes were determined. These values were much lower than the capacity values from the curves because of the presence of some long headways. The presence of the long headways prevented the demand to reach the near capacity conditions. The long headways that indicate lower traffic demand should be eliminated in order to accurately estimate the maximum 15-minute flow rate the work zone can operate.

In order to eliminate the effect of long headways in the calculation of maximum 15-minute flow rate, the “unused” time during which not enough traffic demand was observed should be eliminated from the field data. For a sample of n passenger cars, the total “unused” time is evaluated as follows:

$$T_{U,PC} = \sum_{n} \left(h - 4.0\right); \ \ h \geq 8.0 \text{ sec} \qquad \textit{Equation 4-6}$$

where

$T_{U,PC}$: “Unused” time of the headway of a particular passenger car provided that it keeps a headway of equal to or greater than 8.0 sec (sec),

h: Headway of the passenger car (sec).

Thus, according to Equation 4-6, if a passenger car is maintaining, for instance, a headway of 9.0 sec, then 9.0 – 4.0 = 5.0 sec of its headway is unused time during which there was not enough traffic demand to reach close-to-capacity flow conditions. As mentioned in Section 4.2, it is assumed that a vehicle is in platoon if it maintains a headway of less than 4.0 seconds or a front bumper-to-front bumper spacing of less than 250 ft. otherwise, a vehicle is considered to make free flow in the work zone. Therefore, since 4.0-second headway is on the verge of free-flow, it is assumed that a “conservative” driver would like to maintain a headway of at least 4.0 sec in the work zone. So if a “conservative” driver is maintaining a headway of 7.0 sec in the work zone, there is no extra room in front of him for another “conservative” driver who would also like to keep a headway of at least 4.0 sec. However, if a “conservative” driver is maintaining a headway of 8.0 sec, there is extra room before him for another “conservative” driver who would also like to keep a headway of 4.0 sec. That’s why, it is assumed in Equation 4-6 that vehicle headways shorter than 8.0 sec do not involve any “unused” time. However, all vehicle headways equal to or greater than 8.0 sec have “unused” time since they could have allowed another “conservative” driver in between. Hence, the unused portion of a vehicle headway equal to or greater than 8.0 sec is calculated by subtracting 4.0 sec from the headway since the subtracted 4.0 sec is the minimum headway the “conservative” driver would still like to keep.

When the “unused” time for heavy vehicles is computed, the duration of time it takes for heavy vehicles to travel their extra length should be excluded from the “unused” time computations. Thus, the “unused” time for heavy vehicles is computed as follows:

$$T_{U,HV} = h - \frac{L}{1.47 * S} - 4.0\ ;$$ *Equation 4-7*

where

$T_{U,HV}$: “Unused” time of the headway of a particular heavy vehicle provided that it keeps a headway of equal to or greater than 8.0 sec (sec),

h: Headway of the heavy vehicle (sec),

S: Speed of the heavy vehicle (mph),

L: Extra length of the heavy vehicle compared to passenger cars (ft); L = 45’ can be used on average for trucks.

If one wants to be more precise in computing the unused part of truck headway, one should use the following threshold values for h.

$h - \frac{L}{1.47 * S} \geq 8.0$ sec

However we used a simplified version of it as discussed above.

Once the “unused” time for each vehicle was computed, it was subtracted accordingly from the total duration of the field data so that the effects of insufficient traffic demand were eliminated. Following this, the maximum 15-minute flow rates were computed for both the base and SPE data sets. The results are tabulated in Table 4-3.

Table 4-3. Maximum 15-minute flow rates computed from the base and SPE data sets after the "unused" time for each vehicle is eliminated

Data Set	Lane of Travel	Maximum 15-minute Flow Rate (pcphpl)
BASE	Median	**1891**
	Shoulder	1605
SPE	Median	**1807**
	Shoulder	1523

According to the result in Table 4-3, the maximum 15-minute flow rate that can be maintained in a single lane is 1891 pcphpl when no ITS is deployed in the work zone. As mentioned in Section 4.2, the maximum flow rate that can be maintained in a single lane in the work zone is found as 1900 pcphpl for the base data set as found from the speed-flow curve in Figure 4-5. Thus, both results check well with each other.

Next, Table 4-3 shows that the maximum 15-minute flow rate that can be maintained in a single lane is 1807 pcphpl when SPE is deployed in the work zone. According to Figure 4-5, the maximum flow rate that can be maintained in a single lane in the work zone is 1788 pcphpl for the SPE data set. Therefore, both results check well with each other.

It was stated in Section 4.2 that since the aggregation of the traffic data from the two-lane-open work zone on I55NB (MP=259) was achieved separately for the median lane and the shoulder lane, the capacity values read from Figure 4-5 does not mean that those maximum flow rates can be maintained on both lanes simultaneously. The results in Table 4-3 demonstrate that the maximum 15-minute flow rates in the shoulder lane is significantly lower than those in the median lane because trucks were encouraged to travel in the median lane.

4.4. Sample Calculations

Example: A long-term work zone is located on a four-lane freeway where the binder and the wearing course are repaired. The speed limit in the work zone is 55 mph. The distance between the work activity area and the open lane is 6 ft. The lane width in the work zone is 11.5 ft and the lateral clearance is 4 ft. Moreover, SPE is implemented as speed control measure in the work zone. Estimate the operating speed and operating capacity for passenger cars in the work zone if

1. SPE is deployed in the work zone as a speed-control measure and there are four workers, one paver and one roller in the active work area.
2. SPE is deployed in the work zone as a speed-control measure and there are no workers and no large construction equipment in the work zone,
3. Only standard MUTCD is employed in the work zone to control the vehicle speeds (i.e. no ITS is implemented in the work zone). There are no workers and no large construction equipment in the work zone.

Solutions:

a)

1. The free-flow speed is not measured in the field. Therefore, it is assumed that the free flow speed is equal to the speed limit plus 5 mph. So the free-flow speed (FFS) in the work zone is 55 mph + 5 mph = **60 mph**. The operating speed will be estimated from Equation 3-1 as follows:

$$U_o = FFS - R_{WI} - R_{LW} - R_{LC} - R_{ITS} - R_o$$

2. After the free flow speed is estimated, the speed reduction induced by the SPE can be estimated from Equation 4-1 as follows:

$R_{SPE} = 0.2598{*}FFS_{PC} - 8.4443 = 0.2598{*}60 - 8.4443 = 7.1437$ mph **≈ 7.1 mph**

3. Since the work zone is long-term, the speed reduction due to the work intensity, R_{WI}, is estimated Equation 2-4 from as follows:

$$R_{WI} = 2.6625 + 1.2056 \ln(WI_r)$$

WI_r, the work intensity ratio, is computed from Equation 2-2 as follows:

$$WI_r = \frac{w + e}{p}$$

In this case, there are four workers in the active work area, so w=4. Moreover, there is a paver and a roller in the active work area, so e=2. Since the distance between the open lane and the active work area is 6 ft, p=6. Thus,

$$WI_r = \frac{4 + 2}{6} = 1.0$$

Hence, the speed reduction due to the work intensity is estimated as follows:

$R_{WI} = 2.6625 + 1.2056 \ln(1.0) = 2.6625$ mph ≈ **2.7** mph

4. The lane width in the work zone is given as 11.5 ft. According to Table 3-1 (Chitturi and Benekohal, 2005), the reduction in FFS is 4.4 mph for 11-foot lane width in a work zone and there is no reduction in FFS for 12-foot lane width. So by linear interpolation, the speed reduction for 11.5-foot lane width is estimated as follows:

$$R_{LW} = (4.4\text{mph} - 0.0\text{mph}) * \frac{12.0' - 11.5'}{12.0' - 11.0'} = 2.2\text{mph} .$$

Hence, R_{LW} = **2.2 mph**

5. The lateral clearance in the work zone is given as 4 ft. According to the HCM 2000, the reduction in FFS is 1.2 mph for 4-foot lateral clearance for a four-lane freeway (Exhibit 23-5, p. 23-6). So R_{LC} = **1.2 mph**.

6. There are no other factors reported to influence the operating speed in the work zone, so R_o=0. Since the magnitude of all the speed-reducing factors are known, the operating speed is estimated from Equation 3-1 as follows:

$U_o = FFS - R_{ITS} - R_{WI} - R_{LW} - R_{LC} - R_o = 60 - 7.1 - 2.7 - 2.2 - 1.2 - 0.0 =$ **46.8 mph**

7. When SPE is deployed in the work zone as a speed control measure, the optimum operating speed, $U_{optimum}$, is estimated as 48.1 mph as aforementioned on page 37. Since U_o= 46.8 mph < $U_{optimum}$, the operating capacity, Q, of the work zone is estimated from Equation 4-5 as follows:

$$Q = 271.43 * U^{0.4868} = 271.43 * 46.8^{0.4868} = 1765 \text{ pcphpl}$$

Alternatively, the operating capacity, Q, can be read from the chart as shown in Figure 4-7. First, a horizontal line originating from the operating speed of 46.8 mph is drawn and extended until it intersects with the lower portion of the speed-flow curve at point A. Next, a vertical line originating from the intersection point A is drawn downward until it intersects with the x-axis indicating the flow rate. The flow rate is then read from the x-axis as 1765 pcphpl.

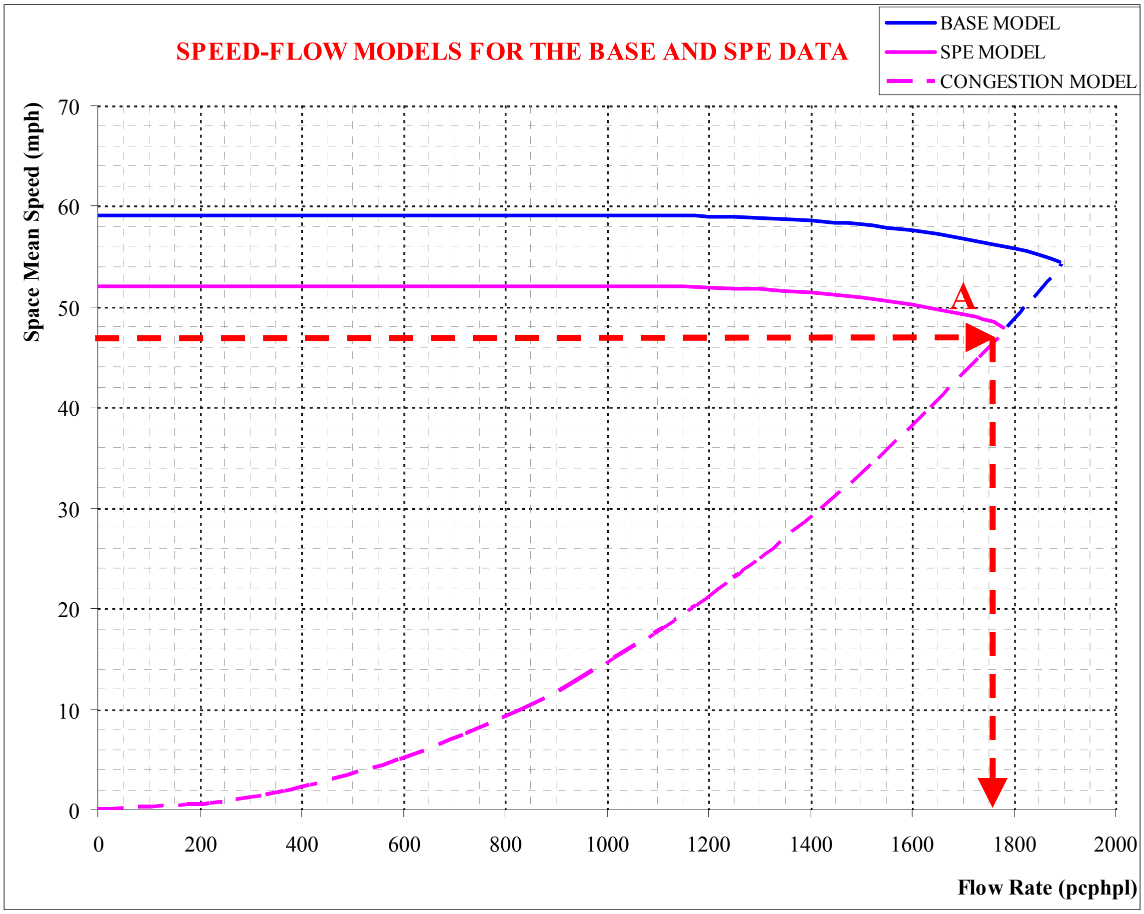

Figure 4-6. Estimating the operating capacity from the operating speed by using lower portion of the speed-flow curve.

b)

1. In this case, R_{WI} in Equation 3-1 is equal to 0.0 because there is no work activity going on in the work zone. Hence, the operating speed in the work zone is estimated from Equation 3-1 as follows:

$U_o = FFS - R_{ITS} - R_{WI} - R_{LW} - R_{LC} - R_o = 60 - 7.1 - 0.0 - 2.2 - 1.2 - 0.0 =$ **49.5 mph**

2. When SPE is deployed in the work zone as a speed control measure, the optimum operating speed, $U_{optimum}$, is estimated as 48.1 mph as aforomentioned on page 37. Since U_o= 49.5 mph > $U_{optimum}$, the operating capacity, Q, of the work zone is estimated from Equation 4-4 as follows:

$$U = FFS - (1.1 * FFS - 15.9) * \left(\frac{Q - 800}{2143 - 4.9 * FFS} \right)^{3.6}$$

$$49.5 = FFS - (1.1 * FFS - 15.9) * \left(\frac{Q - 800}{2143 - 4.9 * FFS} \right)^{3.6} \quad Q = 1675 \text{ pcphpl.}$$

Alternatively, the operating capacity, Q, can be read from the chart as shown in Figure 4-7. First, a horizontal line originating from the operating speed of 49.5 mph is drawn and extended until it intersects with the upper portion of the speed-flow curve for the intelligent work zone (SPE model) at point B. Next, a vertical line originating from the intersection point B is drawn downward until it intersects with the x-axis indicating the flow rate. The flow rate is then read from the x-axis as 1675 pcphpl.

c)

1. In this case, both R_{ITS} and R_{WI} in Equation 3-1 are equal to 0.0 because there is no ITS deployed in the work zone and there is also no work activity going on in the work zone. Hence, the operating speed in the work zone is estimated from Equation 3-1 as follows:

$U_o = FFS – R_{ITS} – R_{WI} – R_{LW} – R_{LC} – R_o = 60 – 0.0 – 0.0 – 2.2 – 1.2 – 0.0 =$ **56.6 mph**

2. When no ITS is deployed in the work zone, the optimum operating speed, $U_{optimum}$, is estimated as 54.4 mph as aforementioned on page 37. Since U_o= 56.6 mph > $U_{optimum}$, the operating capacity, Q, of the work zone is estimated from Equation 4-3 as follows:

$$U = FFS - (1.0 * FFS - 20.6) * \left(\frac{Q - 800}{2208 - 3.9 * FFS} \right)^{3.6}$$

$$56.6 = FFS - (1.0 * FFS - 20.6) * \left(\frac{Q - 800}{2208 - 3.9 * FFS} \right)^{3.6} \quad Q = 1725 \text{ pcphpl}$$

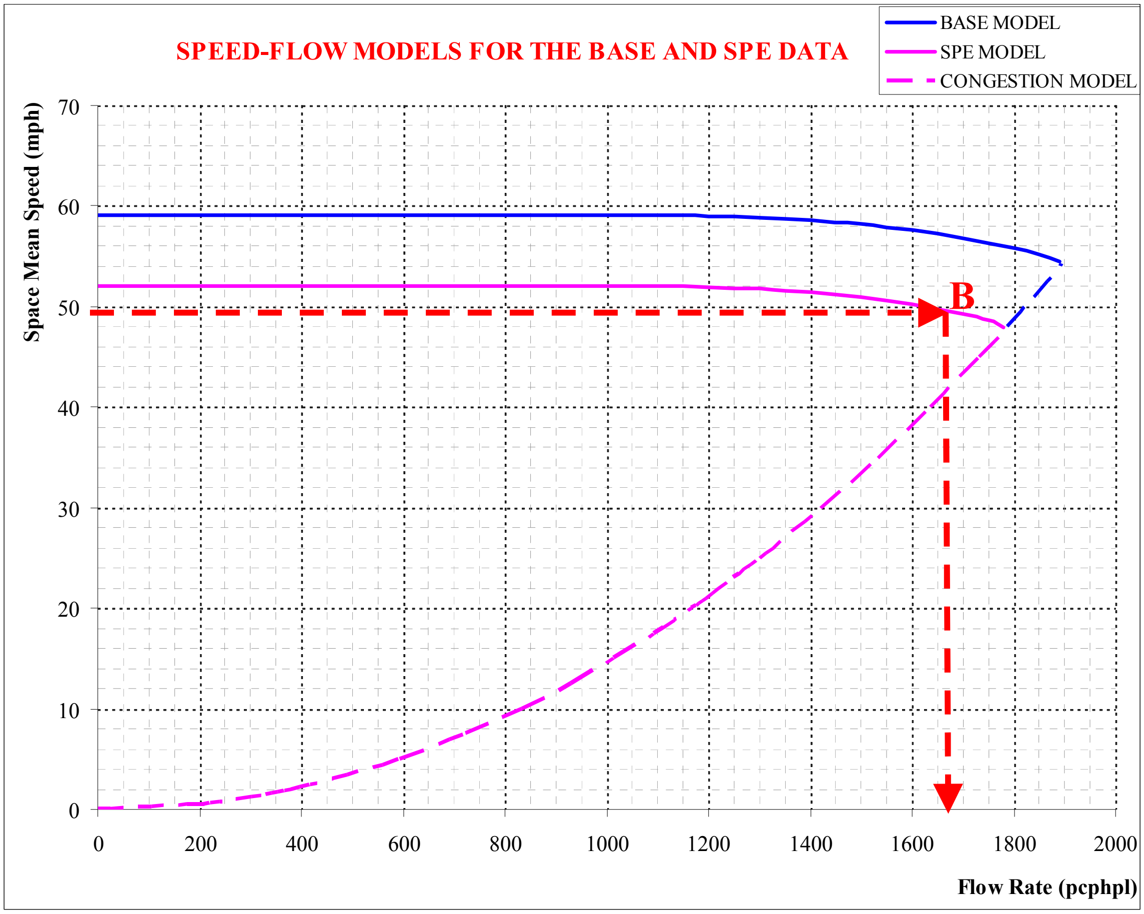

Figure 4-7. Estimating the operating capacity from the operating speed by using the speed-flow curve for the intelligent work zone where SPE is deployed.

Alternatively, the operating capacity, Q, can be read from the chart as shown in Figure 4-8. First, a horizontal line originating from the operating speed of 56.6 mph is drawn and extended until it intersects with the upper portion of the speed-flow curve for the work zone with no ITS (base model) at point C. Next, a vertical line originating from the intersection point C is drawn downward until it intersects with the x-axis indicating the flow rate. The flow rate is then read from the x-axis as 1725 pcphpl.

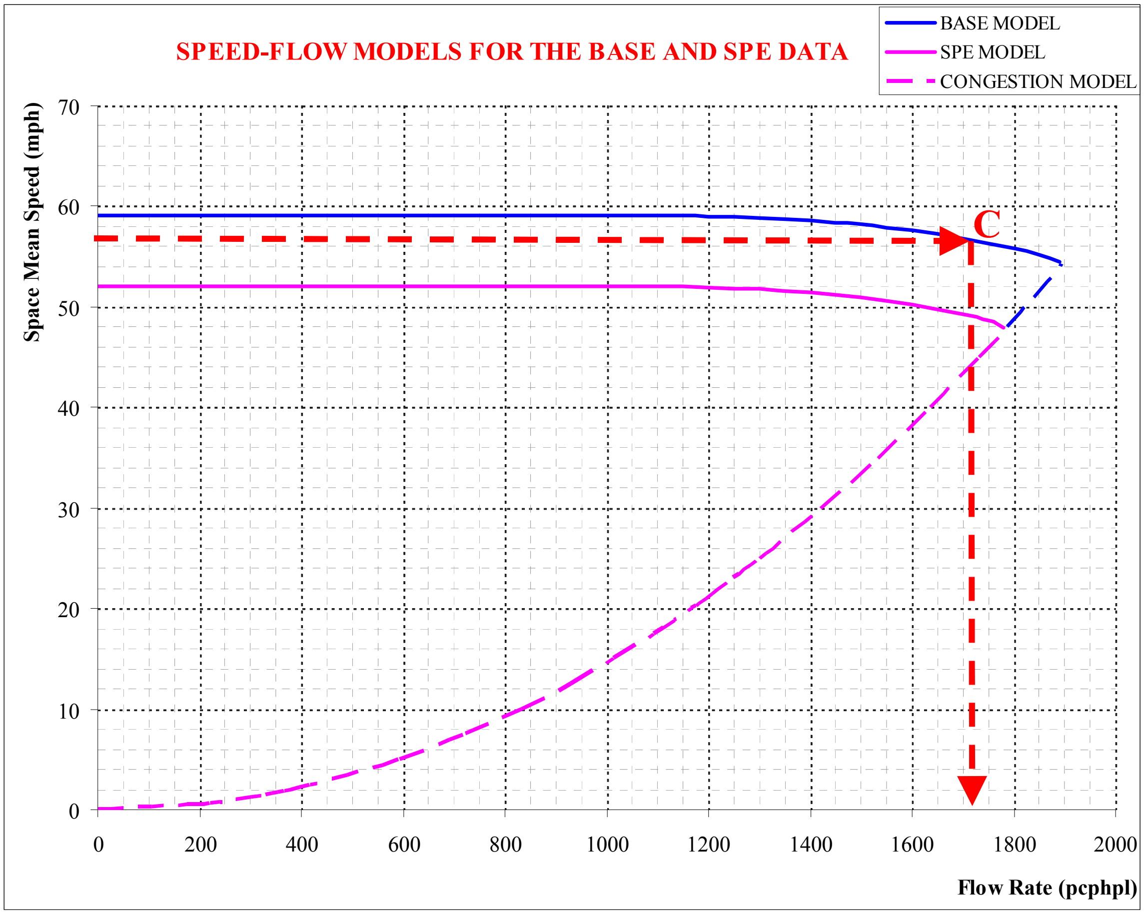

Figure 4-8. Estimating the operating capacity from the operating speed by using the speed-flow curve for the work zone where no ITS is deployed.

CHAPTER 5. CONCLUSION AND RECOMMENDATIONS

This study investigated the effects of implementing ITS in work zones as a speed control measure. While the type of ITS deployed in the work zone can vary, the study explored the effects of SPE on operating speed and operating capacity in intelligent work zones. The operating speed in an intelligent work zone is primarily influenced by the lane width, lateral clearance, work intensity and the type of ITS utilized in the work zone. According to the results regarding the speed-reduction effects of SPE, it led to significant reductions in mean vehicle speeds with the magnitude of the mean speed reduction depending on the free flow speed of vehicles. The results show that the magnitude of mean speed reduction induced by SPE is linearly related to the free flow speed of vehicles before the SPE van becomes visible to them. For instance, for a free flow speed of 50 mph, the mean speed reduction is estimated as 4.5 mph whereas the mean speed reduction is anticipated as 8.4 mph when vehicles travel at a free flow speed of 65 mph.

Once the operating speed in the intelligent work zone is estimated by considering all the speed-reducing factors, the operating capacity of the intelligent work zone can be determined from the relationship between space mean speed and traffic flow rate. In order to determine the operating capacity in the intelligent work zone where SPE was deployed, the fundamental speed-flow curve for the intelligent work zone is established and compared with the speed-flow curve for the same work zone when neither SPE nor another type of ITS was deployed as a speed control measure. According to the results, the use of ITS in the work zone altered the relationship between space mean speed and traffic flow rate by lowering the speeds in the upper (uncongested) part of the speed-flow curve. The use of SPE also brought about a slight reduction of around 100 pcphpl in the maximum per-lane capacity of the two-lane-open work zone compared to when no SPE is utilized. With the speed-flow curve for the intelligent work zone established, one can use the operating speed as an input to accurately estimate the capacity of the intelligent work zone under the prevailing conditions.

Accurate estimation of operating capacity of intelligent work zones gives rise to more effective operation on a real-time basis, more accurate diversion and traveler information for alternate routing and enhanced system reliability. Besides, it brings about improved knowledge on the characteristics of traffic flow in intelligent work zones. In the meantime, the effects of other types of ITS on work zone operating speed and operating capacity have not yet been investigated. Therefore, it is recommended as future research that the outcomes of implementing other types of ITS such as changeable message signs, variable speed limits and dynamic late merge in highway work zones be investigated in order to gain a wider understanding of the traffic flow characteristics in intelligent work zones. It is also recommended to study the speed-flow relationship for work zone where congestion and queue is prevalent.

CHAPTER 6. REFERENCES

Adeli, H. and X. Jiang, *Neuro-Fuzzy Logic Model for Freeway Work Zone Capacity Estimation*, Journal of Transportation Engineering, v 129, n 5, September/October, 2003, p 484-493

Al-Kaisy, A. and F. Hall, *Guidelines for Estimating Capacity at Freeway Reconstruction Zones*, Transportation Research Record, Journal of the Transportation Research Board, vol. 129, No. 5, 2003, pp. 572-577.

Benekohal, R. F., *Speed Reduction Methods and Studies in Work Zones: A Summary of Findings*, Report FHWA-IL/UI-243, September 1992

Benekohal, R. F., A.-Z. Kaja-Mohideen and M. V. Chitturi, *Methodology for Estimating Operating Speed and Capacity in Work Zones*, Transportation Research Record, Journal of the Transportation Research Board, No 1883, TRB, National Research Council, Washington, D.C., 2004, pp. 103-111.

Benekohal, R. F., M. V. Chitturi, A. Hajbabaie, M. H. Wang and J. Medina, *Automated Speed Photo Enforcement Effects on Speeds in Work Zones*, Transportation Research Record, Journal of the Transportation Research Board, No 2055, TRB, National Research Council, Washington, D.C., 2008, pp. 11-20.

Brewer, M. A., G. Pesti, and W. Schneider, *Improving Compliance with Work Zone Speed Limits: Effectiveness of Selected Devices*, Transportation Research Record, Journal of the Transportation Research Board, No 1948, TRB, National Research Council, Washington, D.C., 2006, pp. 67-76

Cassidy, M. J. and L. D. Han, *Proposed Model for predicting Motorist Delays at Two-Lane Highway Work Zones,* Journal of Transportation Engineering, vol. 119, n 1, Jan-Feb, 1993, pp. 27-42

Chitturi, M. V. and R. F. Benekohal, *Effect of Lane Width of Speeds of Cars and Heavy Vehicles in Work Zones,* Transportation Research Record, Journal of the Transportation Research Board, No 1920, TRB, National Research Council, Washington, D.C., 2005, pp. 41-48

Chitturi, M. V., R. F. Benekohal and A.-Z. Kaja-Mohideen, *Methodology for Computing Delay and User Costs in Work Zones*, Transportation Research Record, Journal of the Transportation Research Board, No 2055, TRB, National Research Council, Washington, D.C., 2008, pp. 31-38

Dudek, C. L. and S. H. Richards, *Traffic Capacity Through Work Zones on Urban Freeways*, Report FHWA/TX-81/28+228-6, Texas Department of Transportation, Austin, 1981.

Fatal Analysis Reporting System (FARS), National Highway and Traffic Safety Administration, U.S. Department of Transportation, http://www.fars.nhtsa.dot.gov, Mar. 17, 2005.

Garber, N. J. and S.T. Patel, *Control of vehicle speeds in temporary traffic control zones (work zones) using changeable message signs with radar*, Transportation Research Record, Journal of the Transportation Research Board, No 1509, TRB, National Research Council, Washington, D.C., Jul, 1995, pp. 73-81

Garber, N. J. and S. Srinivasan, *Influence of exposure duration on the effectiveness of changeable-message signs in controlling vehicle speeds at work zones*, Transportation Research Record, Journal of the Transportation Research Board, No 1650, TRB, National Research Council, Washington, D.C., Nov, 1998, pp. 62-70

Garber, N. J. and M. Zhao, *Distribution and Characteristics of Crashes at Different Work Zone Locations in Virginia*, Transportation Research Record, Journal of the Transportation Research Board, No 1794, TRB, National Research Council, Washington, D.C., 2002, pp. 19-28

Highway Capacity Manual (HCM), TRB, National Research Council, Washington, D.C., 2000.

Kang, K, G. Chang and N. Zou, *Optimal Dynamic Speed-Limit Control for Highway Work Zone Operations*, Transportation Research Record: Journal of the Transportation Research Board, No. 1877, TRB, National Research Council, Washington, D.C., 2004, pp. 77–84.

Kang, K., G. Chang and J. Panacha, *Optimal Dynamic Speed-Limit Control for Highway Work Zone Operations*, Transportation Research Record: Journal of the Transportation Research Board, No. 1948, TRB, National Research Council, Washington, D.C., 2006, pp. 86-95.

Kim, T., D. J. Lovell and J. Paracha, *A New Methodology to Estimate Capacity for Freeway Work Zones*, Preprints of the Transportation Research Board 80th Annual Meeting (CD-Rom), Transportation Research Board, Washington, D.C, 2001.

Kwon, Eil, D. Brannan, K. Shouman, Cassandra Isackson, and Bernie Arseneau, *Development and Field Evaluation of Variable Advisory Speed Limit System for Work Zones*, Transportation Research Record, Journal of the Transportation Research Board, , No 2015, Maintenance Operations: Work Zones, Pavement Markings, and Weather, National Research Council, Washington, D.C., 2007, pp. 12-18

Mattox III, J. H., W. A. Sarasua, J. H. Ogle, R. T. Eckenrode and A. Dunning, *Development and Evaluation of Speed-Activated Sign to Reduce Speeds in Work Zones*, Transportation Research Record, n 2015, Maintenance Operations: Work Zones, Pavement Markings, and Weather, 2007, pp. 3-11

McCoy, P.T., J.A. Bonneson and J.A. Kollbaum, *Speed Reduction Effects of Speed Monitoring Displays with Radar in Work Zones on Interstate Highways*, Transportation Research Record, Journal of the Transportation Research Board, No 1509, TRB, National Research Council, Washington, D.C., Jul, 1995, pp. 65-72

Mohan, S. B. and P. Gautam, *Cost of Highway Work Zone Injuries*, Practice Periodical on Structural Design and Construction, v 7, n 2, May, 2002, Construction Safety, pp. 68-73

National Work Zone Safety Information Clearinghouse, *Fatalities in Motor Vehicle Traffic Crashes by State and Construction/Maintenance Zone (2007),* http://www.workzonesafety.org/crash_data/workzone_fatalities/2007, 2008

Pesti, G. and P. T. McCoy, *Long-term effectiveness of speed monitoring displays in work zones on rural interstate highways*, Transportation Research Record, Journal of the Transportation Research Board, No 1754, TRB, National Research Council, Washington, D.C., 2001, pp. 21-30

Rakha, H., M. Farzaneh, M. Arafeh and E. Sterzin*, Inclement Weather Impacts on Freeway Traffic Stream Behavior*, Transportation Research Record, Journal of the Transportation Research Board, No 2071, TRB, National Research Council, Washington, D.C., 2008, pp. 8-18

Salem, O.M., A. M. Genaidy, H. Wei, and N. Deshpande, *Spatial Distribution and Characteristics of Accident Crashes at Work Zones of Interstate Freeways in Ohio*, IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC, Proceedings of ITSC 2006: 2006 IEEE Intelligent Transportation Systems Conference, pp. 1642-1647

Sarasua, W. A., W. J. Davis, M. A. Chowdhury and J. H. Ogle, *Estimating Interstate Highway Capacity for Short-Term Work Zone Lane Closures*, Transportation Research Record, Journal of the Transportation Research Board, No 1948, TRB, National Research Council, Washington, D.C., 2006, pp. 45-57

U.S. Department of Energy, *Temporary Losses of Highway Capacity and Impacts on Performance*, Oak Ridge National Laboratory (ORNL/TM-2002/3), May 2002

U.S. Department of Transportation, Federal Highway Administration, *A Snapshot of Peak Summer Work Zone Activity Reported on State Road Closure and Construction Websites*, Washington, D.C., August 2002

Yulong, P. and D. Leilei, *Study on Intelligent Lane Merge Control System for freeway work zones*, IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC, 10th International IEEE Conference on Intelligent Transportation Systems, ITSC 2007, 2007, p 586-591

Zech, W. C., S. B. Mohan, and J. Dmochowski, *Evaluation of Messages on Changeable Message Signs as a Speed Control Measure in Highway Work Zones*, Practice Periodical on Structural Design and Construction, v 13, n 1, 2008, pp. 11-18