

**INVESTIGATION OF FACTORS AFFECTING CAPACITY AT RURAL
FREEWAY WORK ZONES**

by

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ABSTRACT

Traffic management in freeway construction zones is a challenging task to traffic engineers. Capacity reduction in the work zone is a one of the causes of the problems. Although many past works investigated the capacity problem at work zone locations, only few of them quantified the capacity factors. The presented study investigated potential capacity factors to develop capacity prediction models. The investigated factors include rain and wind, heavy vehicles, the type of lane drop (left or right), police presence, and presence of a novel traffic control system called Indiana Lane Merge System (ILMS). The capacity study was limited to two-lane roadways on rural freeway with one lane dropped.

The results indicate that rainfall, heavy vehicles, police presence, and ILMS presence reduce capacity of work zones. The magnitude of reduction caused by rain and heavy vehicles is similar to the reduction observed on freeway sections without work zones. The reducing effect of ILMS is limited (5-6%). This effect may be temporary and may diminish with drivers' growing familiarity with the system. The strongest reduction (14%) was observed during police presence near the work zone.

Keywords: work zone, capacity, freeway, ILMS, rain, heavy vehicles

INTRODUCTION

Managing traffic in construction zone areas is still a big challenge. Serious problems that need to be addressed are the deterioration of highway safety and the excessive delays. These problems originate inside the work zones and sometimes on the work zone approaches if one or more traffic lanes are closed. The main source of delays in a work zone is the capacity reduction caused by the road construction.

The objective of this study is to investigate capacity factors for work zones on rural freeways where some lanes are temporarily closed. The following part of the introduction briefly summarizes current knowledge on the subject to show a need for more research.

The 1997 Highway Capacity Manual (1) summarizes in Chapter 6 the past research on the effect of work zones on freeway capacity. HCM notes that work zone capacity depends on the nature of work, the number and size equipment at site, and the location of equipment and crews with respect to moving lanes of traffic. The manual provides a summary of observed capacities for some typical construction and maintenance operations.

Several authors have measured and analyzed capacities of work zones. Richards and Dudek (2) measured capacity of urban freeway work zones. They measured traffic volumes when queues were formed upstream from the lane closures. The capacity was influenced by the lane closures and by the work zone activities (trucks, presence of workers, etc.). They compared the capacities of work zones with and without work crews in view.

Cunagin and Chang (3) investigated the effect of trucks on freeway vehicle headways during off-peak flow conditions. They concluded that the presence of trucks in the traffic stream was associated with an increase in the mean headway, which indicated capacity reduction. Truck drivers seemed to keep longer space headway than do car drivers. This effect was investigated for freeway open sections and not for work zones.

Other potential factors of capacity are harsh weather conditions including heavy rain and strong wind. Jones and Goolsby (4) found that presence of rain reduced capacity by about 14 percent. HCM, 1997 (1) states that 10 to 20-percent capacity reduction due to rain is typical and that higher reductions are possible. HCM also recommends that these effects be considered in any facility analysis, particularly when such conditions are common. As in the case of heavy vehicles, this effect has not been investigated for work zones.

A work zone entry section with a dropped lane is critical for traffic smoothness and safety. Some drivers try to avoid dense traffic in the continuous lanes and approach the taper in the discontinued lane up to the point where a lane change maneuver becomes difficult and risky. An early work on the effect of lane closures on freeway capacity was done by Nemeth and Roupail (5) who used a microscopic computer simulation model. They modeled merging behavior of drivers influenced by traffic control devices and by drivers' preferences where to merge. This research has concluded that there is a potential for capacity increase by encouraging drivers to merge further upstream from the taper.

A new traffic control system, Indiana Lane Merge System, has been proposed by Indiana Department of Transportation (INDOT) to improve the use of traffic lanes on work zone approaches. The idea of ILMS was similar to what was postulated by Nemeth

and Roupail (5) - to reduce the number of aggressive lane changes at the taper by encouraging drivers to switch lanes well upstream of the discontinuous lane taper. The ILMS consists of a series of static and dynamic signs that create a variable *no passing zone* in advance of the work zone. The signs are turned on in response to congestion in the continuous lanes. A detail description of the system can be found in Tarko et al. (6). The impact of ILMS on capacity was investigated in the presented study.

According to the authors' knowledge, there are additional conditions that may affect work zone capacity and that have not been investigated yet. They are: wind, police, and which lane is dropped - on the left or right side of the roadway. In heavy wind, drivers may have difficulties with keeping their automobiles, particularly large trucks, on the roadway. The effect of police on the work zone capacity was included in this research because INDOT considers potential benefits of police presence in work zones.

Traffic in some work zones is managed by closing one roadway and converting the other roadway into a two-way road. The traffic from the close roadway is diverted to the two-way roadway through a crossover. Traffic engineers have to decide which lane, left or right, will be tapered off on before traffic is directed to the crossover. This study investigates the effect of this decision on the work zone capacity.

DATA COLLECTION

To investigate all the characteristics discussed in the introduction, data was collected at a selected work zone that was believed to well represent typical rural construction zone with discontinued lanes. The data were collected for an extended period to be able to cover all temporary characteristics (rain, wind, presence of ILMS,

police). Due to a high cost of data collection, approximately \$20,000, we could not effort to collect data at other locations.

In this study, the following data were to be collected:

1. Traffic volume,
2. Percentage of heavy vehicles,
3. Presence of ILMS,
4. Presence of rain,
5. Wind speed,
6. Type of lane drop,
7. Presence of police.

The experimental test bed for the study was the I-65 work zone near West Lafayette, Indiana. The work started in March 1999 and continued for five months until July. The test bed provided two sites: northbound and southbound roadways where lanes were dropped. The work zone segment extended approximately from the 178 milepost near SR-43 interchange to the 193 milepost near US-231 interchange. The work involved rehabilitation and resurfacing of the pavement and hence, it involved intensive activity and presence of construction equipment and personnel. The daily traffic ranged from about 26,000 veh/day in the weekdays (Monday through Thursday) to about 42,000 veh/day during the weekends. Congestion was observed only during the weekends, on Fridays on the I-65 southbound approach and on Sundays on the I-65 northbound approach. The I-65 work zone can be considered a quite typical for Indiana long-term rural construction site.

The main data required for the analysis was traffic volume and speed data. Traffic speed and volume were collected for a four-month period from April 1999 to July 1999. The data was collected using a series of taped-down loop detectors installed on both the entrances to the work zone (Figure 1). The volumes were measured at the location close to the taper where a bottleneck was expected. The 15-minute detector-reporting interval was originally selected, but was changed to 20-minutes due to data storage limitations.

The traffic data was collected continuously for a three-month period when congestion occurred only during some hours. It became necessary to identify intervals with capacity conditions. We used the speeds measured at the spots located upstream of the taper where congested traffic was expected. A sudden drop of speed indicated the capacity conditions. Determination of capacity is illustrated on the volume-speed graph in Figure 2. The graph shows a rapid drop of speed, then an extended period with lower speeds, and then a sudden rise of speeds that marks the end of capacity conditions. The presented speeds during capacity conditions do not reflect the actual speeds properly since the lowest speed bin was set at 0-30 mi/h.

As has been mentioned, an observation includes traffic volume measurements in 20- minute intervals. Traffic counts obtained for capacity intervals were converted to hourly capacities by multiplying the counts by factor three. Once all the capacity volumes had been calculated, additional data including weather, heavy vehicle percentages, wind speed, and the status of ILMS were collected to extend the number of investigated characteristics. The traffic data was collected at the selected site without and with ILMS. After ILMS was turned on or turned off, about two weeks were given to drivers to adjust to the new situation before data was collected. The loop detectors installed for the volume

and speed measurements had the capability of classifying vehicles. This feature was used to obtain the percentage of heavy vehicles. The weather information about rain and wind speed during the study period was obtained from the Earth and Atmospheric Sciences Department at Purdue University, West Lafayette. The weather station was located 5 miles from the I-65 work zone.

DATA ANALYSIS

After removing incomplete observations, the final sample had 182 observations. The collected sample of observations was analyzed using four methods: descriptive summary, covariance analysis, linear regression, and non-linear regression.

Preliminary Analysis

Table 1 shows results of a preliminary analysis. The average value of capacity obtained for the I-65 work zone is 1320 veh/hr. Table 1 indicates that all the investigated characteristics, except police, are well represented in the sample. For the police variable, there are only 13 observations with police presence. This could result in an insignificant estimate of the police effect if it was weak.

The wide range of capacity values in Table 1 and short-term variability of capacity in Figure 2 indicate that capacity is not stable. The reasons for the capacity instability are not fully clear. However, from the field observations and from the video data, the authors noticed that the valleys in the capacity profile match the time intervals when stop-and-go conditions occurred. The sequence of breakdowns might be caused by aggressive merging at the taper that leads to backward congestion waves. The authors

noticed particular truck drivers' behavior that sometimes preceded a traffic breakdown. To prevent being passed by other vehicles, two trucks move side by side and block both the lanes. The trucks continue in the same fashion until the taper, where the truck in the discontinued lane merges into the open lane. The vehicles behind the trucks form two lanes. Those in the closed lane are left with no choice but to aggressively merge at the taper. This leads to a very dense platoon of traffic entering the work zone. Inside the work zone, vehicles spread along to regain safe distances. This may create a backward shock wave eventually leading to the stop-and-go conditions on the approach.

Analysis of Covariance

Some of the explanatory variables are binary variables while the others are continuous variables. Therefore, the authors decided to use Analysis of Covariance (ANCOVA) to investigate the effects represented by single variables and the joint effects represented by multiple variables (interactions). Only two-way interactions were included in the study since interactions of higher order are somewhat difficult to interpret. The applied ANCOVA model can be stated as follows,

$$Y_{ijkmhwo} = \mu_{\dots} + M_i + R_j + LD_k + P_m + H(X_h - \bar{X}_h) + WS(X_w - \bar{X}_w) + (MR)_{ij} + (MD)_{ik} + (MP)_{im} + (RD)_{jk} + (RP)_{jm} + (DP)_{km} + \varepsilon_{ijkmhwo}, \quad (1)$$

where:

M_i = main effect of presence of ILMS,

i = for ILMS present, $i = 0$ for ILMS not present,

R_j = main effect of rain,

$j = 1$ if it is raining, $j = 0$ otherwise,

LD_k = main effect of type of lane drop,
 $k = 0$ if left lane dropped, $k = 1$ if right lane dropped,
 P_m = main effect of police variable,
 $m = 0$ if police not present, $m = 1$ otherwise,
 H = estimation parameter for percent of trucks,
 X_h = percent of heavy vehicles,
 WS = estimation parameter for wind speed,
 X_w = wind speed in km/hr,
 MR, MD , etc. = two-way interaction effects ,
 $\varepsilon_{ijklmhw}$ = error term, $N(0, \sigma^2)$,
 μ_{\dots} = overall mean.

The statistical modeling was performed using the Statistical Analysis Software (7). The first step was to identify the presence of outliers in the sample. The studentized residual values were compared with Bonferroni critical value (here = 3.7) and the largest studentized residual value was less than the critical value. Hence, it was concluded that no outliers were present. Independent variables were added at each step and the variables were tested for their statistical significance and the stability of the standard errors of parameter estimates were observed. The change in standard errors was tested by bringing in and taking out independent variables. The final variables, which were included in the model, had a significant impact on the model. The parameters associated with the final independent variables were stable under covariates inclusion and exclusion.

For testing statistical significance, F-values associated with the independent variables were noted. The (Pr>F) value is the probability that the estimated F is greater than or equal to the obtained estimate when the true value is zero (no effect). A significance level of 5% was adopted for testing the null and alternate hypotheses. If the

(Pr>F) value was less than 5% then the variable was accepted, else it was rejected. The list of variables, which satisfied this criterion are given in Table 2.

ILMS, rain, police, and heavy vehicles turned out to be the only significant variables at the 5 % significance level. Type of lane drop and wind speed turned out to be insignificant. ANCOVA has showed that all the two-way interaction effects are insignificant. This implies that all the main effects are independent of each other.

Regression Additive Model

In the next step, a regression model was developed to provide a more convenient and frequently used tool for predicting work zone capacities. Following the findings from ANCOVA, only the main effects were included.

Capacity was assumed linearly dependent on explanatory variables. As with ANCOVA, the variables were tested for their significance at the 5% significance level.

The results shown in Table 3 are as anticipated. The obtained model is:

$$C = 1433 - 76 M - 140 R - 196 P - 4.04 H, \quad (2)$$

$$R^2 = 0.853, \text{ Adj. } R^2 = 0.849, \sigma(\varepsilon) = 48 \text{ veh/hr,}$$

where:

C = capacity of the work zone expressed in veh/hr,

M = indicator variable for ILMS,

R = indicator variable for rain,

P = indicator variable for police presence,

H = percentage of heavy vehicles in the traffic stream.

The t-ratios, p-values, and the standard errors of the estimates have also been included. A plot comparing the predicted and the observed values of capacity is presented in Figure 3. The R^2 value obtained for the model is 0.849, which indicates that the model is reasonably good and has a considerable predictive power.

Regression Multiplicative Model

In the regression model, the capacity is expressed as an additive formula, where the effects of each variable are added to the capacity under ideal conditions. Another way, used in the Highway Capacity Manual (1), is to adjust the ideal capacity with adjustment factors. From the previous analysis, it has already been established that only the effects of ILMS, rain, heavy vehicles, and police should be included in the model. Hence, the expected adjustment equation for capacity on work zones is:

$$C = C_0 f_M f_R f_H f_P, \quad (3)$$

where:

C = capacity in one direction for prevailing roadway, traffic control and traffic conditions,

C_0 = capacity under ideal conditions. The ideal conditions in this case are defined as with no traffic control (no ILMS), under normal weather conditions (no rain), no police presence and no trucks ,

f_M = adjustment factor for ILMS,

f_R = adjustment factor for rain,

f_p = adjustment factor for police,

f_H = adjustment factor for heavy vehicles in the traffic stream, computed as

$$f_H = \frac{1}{1 + P_H(E_H - 1)}, \quad (4)$$

P_H = proportion of heavy vehicles in the traffic stream, expressed as decimal,
and E_H = passenger car equivalent for heavy vehicles.

The model has been fit by minimizing the error sum of squares $\sum_i (C_{obs} - C)_i^2$, where C_{obs} is measured capacity and C is the estimate yielded for interval i by Equation 3 with embedded Equation 4. The Newton-Raphson convergence technique was used for obtaining the best-estimated values. The initial solution used was: $C_0 = 1320$, $f_M = f_R = f_P = 1$, $E_H = 2$.

The optimal estimates for the adjustment factors and the ideal capacity are given in Table 4. The estimated value of ideal capacity corresponds very closely to the intercept (ideal capacity) obtained from the regression model. The standard error of estimation, 53 veh/hr is close to the value obtained in the regression model, 48 veh/hr.

DISCUSSION

The results indicate that most of the investigated variables except type of lane drop and wind speed are significant. All the significant variables represent effects that reduce capacity. The signs of all variables in the additive model except ILMS and police are as expected. Although the discussion of the results refers mainly to the additive model, similar conclusions could be drawn based on the multiplicative model.

The intercept value C_0 of 1430 veh/hr is the capacity under conditions that are defined ideal. These conditions are characterized by lack of precipitation, no ILMS, police absence, and no heavy vehicles. The ideal capacity is nearly 100 veh/hr higher than the average sample value 1320 veh/hr.

A rainfall reduces capacity as expected. On an average, the reduction in capacity is 140 veh/hr or about 10 %. The reduction is close to the values quoted by the Highway Capacity Manual (1) for freeways without work zones. It should be kept in mind that the obtained capacity equation describes non-winter conditions. Snowy conditions should not be confused with non-rain conditions.

As expected, heavy vehicles reduce the capacity. The estimated reduction is about 4.0 for each 1% increase in truck percentage. This reduction seems to be small if keeping in mind the observed behavior of trucks that might cause some of the traffic breakdowns. This contradiction can be explained with the fact that the result of the breakdown caused by trucks in one interval may persist during following intervals. This lasting effect of trucks reduces the covariance between the percent of trucks and the capacity observed during the same interval. The calibration of the multiplicative model in Equations 3 and 4 has yielded a truck equivalency factor $E_H = 1.4$ (see Table 4). The obtained value compares well with the equivalent factor of 1.5 recommended by HCM for freeways without work zone and in level terrain.

Indiana Lane Merge System (ILMS) was expected to increase the capacity due to reduced number of aggressive merging at the taper. The results indicate that ILMS reduces the capacity by about 76 veh/hr or about 5 % of capacity. Although the reduction seems to be limited, it is significant from the statistical and practical standpoints. One

reason of the capacity reduction hypothesized by the authors is the drivers' reaction to the new signs. Drivers tend to be more careful and thereby tend to slow down and keep longer headways. The two-week period given to drivers for accommodation to the new system might make no difference since all the congestion cases occurred during weekends and special events when majority of drivers were not regular users of the road. Since ILMS is a new system not widely used, there is a chance that this effect will weaken in a long run when the drivers become more familiar with the system.

The police effect is even more surprising than the ILMS effect. A strong compliance rate to the ILMS DO NOT PASS signs was observed during the police presence. At the same time, the capacity was lower by nearly 200 veh/h. Direct observations and measurements indicated lower speeds and longer gaps between vehicles. Apparently, drivers become extra cautious when they see police.

The effect of type of lane drop (left or right) on capacity was found insignificant. In other words, the study has shown that the side at which lane is dropped had no effect on the capacity of the investigated work zone. This result is valuable to roadway management personnel, who are fraught with the problem which lane should be dropped.

Strong wind was believed to reduce capacity. In presence of strong winds, drivers of tall vehicles are expected to keep longer gaps and drive slowly. Although, the results do not confirm the above expectations, it should be noted that the wind speeds in the sample were on the lower range. The strongest wind was about 24 km/h.

CLOSURE REMARKS

The primary aim of this paper was to analyze the effect of Indiana Lane Merge System on capacity of freeway work zones. Although, the system was expected to improve capacity, the results indicate that the new system reduces capacity by about 5%. The authors attribute this reduction to the unfamiliarity of the drivers with the new system. We hope that this effect is temporary.

The authors tried to re-address some other capacity factors such as rain and heavy vehicles. As expected, these conditions have a reducing effect on capacity. Revealing is the finding that the magnitude of these effects is similar to the one indicated by other authors for regular road conditions not affected by work zones.

The effect of the presence of police on the capacity of freeway work zones was also investigated. In spite of a stronger compliance rate to the ILMS signs, there was a significant reduction in capacity (14 %). This can be attributed to the extra cautious behavior of drivers. Similar effect should be expected for work zones without ILMS.

A valuable insight was gained on driver behavior in response to queue presence. On approaches to work zones, truck drivers frequently block both the lanes causing additional congestion. Further, drivers that use the discontinued lane, comply with the DO NOT PASS signs reducing their speeds. Many of them still wait on the discontinued lane and merge at the last moment. New traffic regulations are needed to enable using an enforceable direction, MERGE in lieu of DO NOT PASS.

ACKNOWLEDGEMENT

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Table 1 Descriptive statistics of the investigated characteristics

Continuous variables				
Variable	Maximum	Minimum	Average	Standard Deviation
Capacity , veh/hr	1591	1000	1320.57	118.99
Percentage of heavy vehicles	24.32	0.65	8.85	3.97
Wind speed, km/hr	24	3.2	7.05	3.70
Discrete variables				
Value	Rain	ILMS	Type of lane drop	Police
1	59	62	71	13
0	123	120	111	169

Table 2 F- values and p-values for the explanatory variables in the covariance analysis

Source	DF	Type III SS	Mean Square	F value	Pr > F
<i>H</i>	1	23912.90	23912.9	10.4	0.0016
<i>R</i>	1	161394.08	161394.1	70.19	0.0001
<i>M</i>	1	73630.19	73630.19	32.02	0.0001
<i>P</i>	1	221858.66	221858.7	96.48	0.0001

Table 3 The statistical estimates of the explanatory variables, regression additive model

Term	Slope	Standard Error	t-ratio	p-value
1	1430	11.9	120.9	0.000
M	-76.3	13.5	-5.7	0.000
R	-139.5	16.7	-8.4	0.000
H	-4.0	1.3	-3.2	0.002
P	-196.0	20.0	-9.8	0.000

Table 4 Estimates of the ideal capacity and adjustment factors, multiplicative regression model

Parameter	Estimated Value
C_0	1440
f_M	0.94
f_R	0.91
f_P	0.86
E_H	1.4

Standard Deviation = 52.5 veh/hr

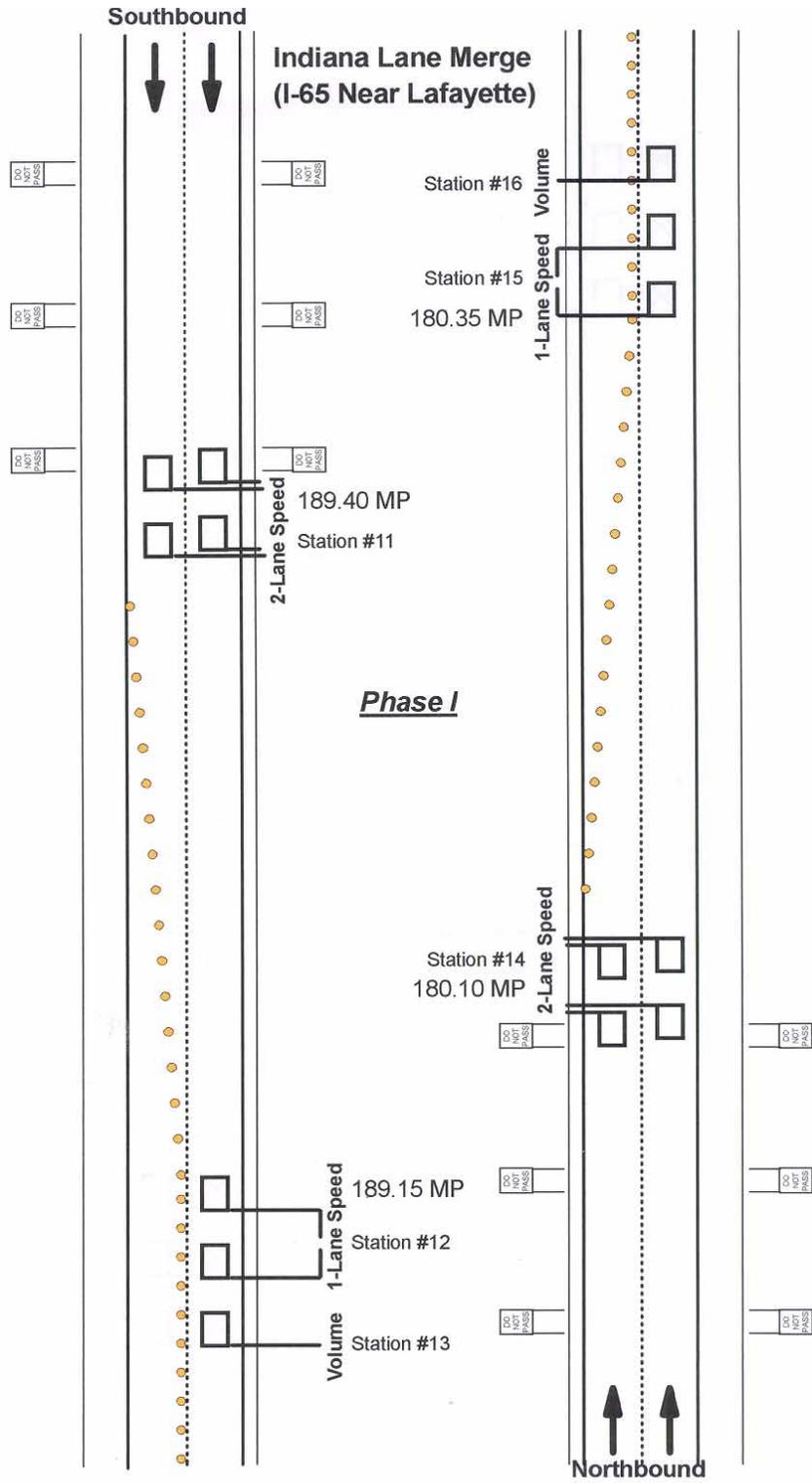


Figure 1 Layout of loop detectors for volume and speed measurements

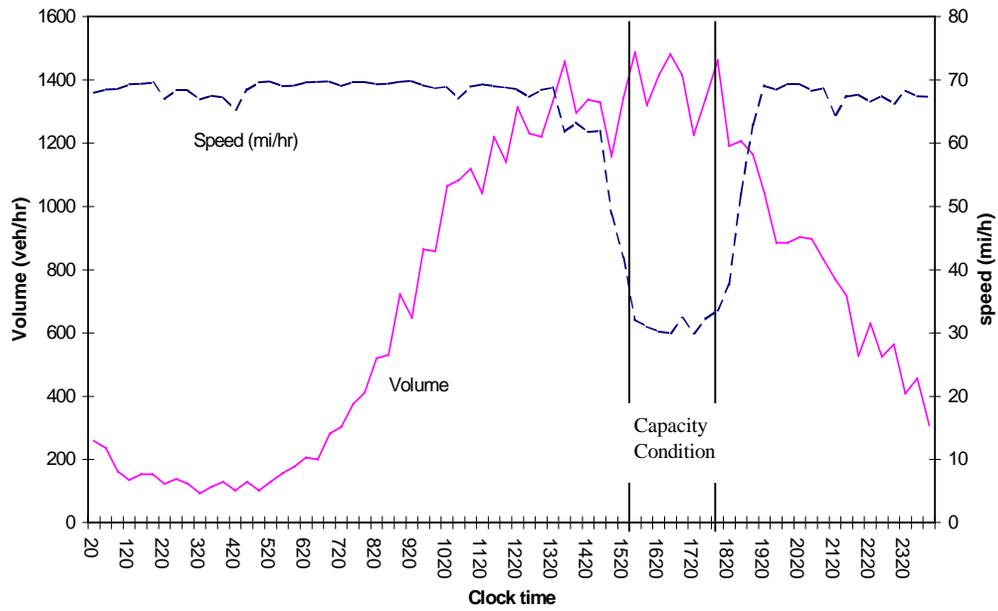


Figure 2 Volume–speed profile for identifying capacity conditions

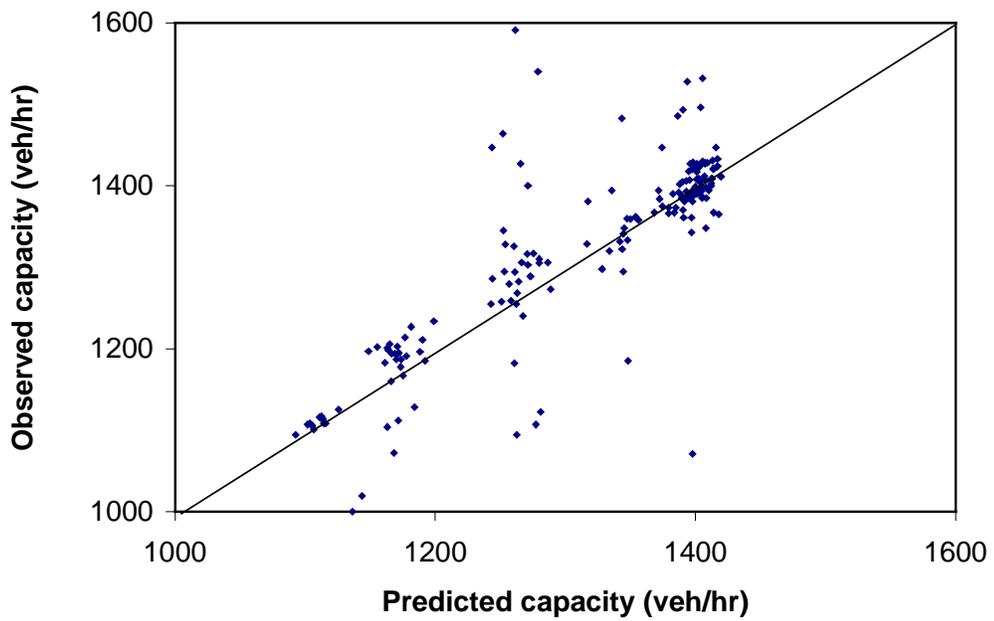


Figure 3 Predicted versus observed capacity values, additive regression model