

Safety, Delay and Capacity of Single Lane Roundabouts in the United States

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Abstract

Roundabouts are a form of at-grade intersection control that is used frequently around the world and is becoming popular in the U.S. Roundabouts are being used to replace two-way and all-way stop controlled intersections (TWSC, AWSC) and traffic signals in the U.S. Roundabouts have also been recently used in Vail, Colorado to improve an existing stop-controlled freeway interchange system. In this study, five single lane roundabouts are studied to assess their safety and operational performance. All five sites were stop-controlled before roundabouts were installed, and overall the sites saw a reduction in accident frequencies, rates and also control delay.

Aside from reviewing the safety and delay data before and after installation of the roundabouts, this study also compares field-measured control delay to that predicted by SIDRA. SIDRA is an analytically based software package that can analyze at-grade sign and signal controlled intersection as well as roundabouts. This study will help agencies better understand its ability to predict delay at American roundabouts. Finally, findings are presented regarding the accuracy of the roundabout capacity model contained in the 1997 update to Chapter 10 of the Highway Capacity Manual (HCM). Due to the lack of roundabout entries that are operating at capacity in the U.S., an approximation of potential capacity based on available gaps in the circulating stream was made. These findings indicate that the manual may be optimistic in its prediction of capacity of single lane roundabouts in the U.S., however it should be noted that the lack of roundabouts entries operating under capacity in the U.S. only allow for an approximation to be made at this time of field capacity.

Key words: roundabout, safety, delay, capacity

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INTRODUCTION

Roundabouts are a form of at-grade intersection control that is becoming increasingly popular in the United States. Roundabouts are similar to traffic circles, popular in the early 1900's, however they include design and operational improvements that enhance their performance as compared to traffic circles. Roundabouts differ from traffic circles by including the following in their design:

- ◆ Yield on entry
- ◆ Deflection on approaches
- ◆ Flared entries (1)

Yield on entry or “priority rule” requires entering vehicles to yield to drivers in the circulating roadway. Priority rule was adopted in Britain in the 1960s and since that time many other countries have adopted this practice, including the United States (2). Prior to the adoption of the priority rule, many rotary junctions operated with yield signs in the circulating roadway often resulting in grid-lock. Grid-lock refers to the instance when entering vehicles cannot enter the circulating roadway and the circulating roadway cannot circulate due to the never ending stream of entering drivers. By instead forcing entering drivers to yield to circulating drivers, as roundabouts do, excess demand is placed on the approaches and not within the limited area of the circulating roadway. An example of requiring yield on entry at an American roundabout is shown in Figure 1.

Deflection is the second design element that is unique to roundabouts. Deflection is a design technique applied to the entries of roundabouts that helps to smooth the transition between straight approaches and circulating roadways of roundabouts. This transition also helps to alert drivers to a change in the roadway ahead and slows the entry of vehicles. Deflection is often enhanced through the use of splitter islands on the approach. Splitter islands can be striped areas, areas defined by raised reflector buttons or raised concrete islands. Splitter islands provide drivers with more clues as to the changing roadway, and alerts them to take appropriate actions. Splitter islands also serve as refuge islands for pedestrians crossing an approach of a roundabout. Figure 2 illustrates the use of deflection in an American roundabout.

The final design element that is sometimes applied to roundabouts is flared entries. Flared entries are used to increase capacity at the approach by increasing the number of entering lanes to the roundabout. The idea behind flared approaches is that if intersections or nodes are designed to accommodate more vehicles, than the width of the approach roadways upstream and downstream can be kept to a minimum. Some experts believe that intersections are the heart of capacity problems not the approach lanes. Flared approaches are often associated with British design techniques. Comparing single lane entering roundabouts to flared approach roundabouts, it is easy to demonstrate the increased number of conflict points in the later design. Because of this, two states, Florida and Maryland, who are actively building roundabouts, have decided not to allow flared approaches on their roundabouts. Figure 3 is a photo of the North roundabout in Vail, Colorado in which flared approaches exist.

Roundabouts in the U.S.

In 1994 the first roundabout freeway interchange in Vail, Colorado opened with much success. While the Vail roundabouts have been successful in improving traffic conditions, the use of roundabouts at high volume intersections in the U.S. is relatively rare. Currently the primary use of roundabouts, in the U.S., is as a replacement of two-way or all-way stop controlled intersections. Through surveys of local and state agencies, it appears that many agencies would like to test the effectiveness of roundabouts at lower volume intersections before installing them at high volume intersections. Through these same surveys, the most often stated reason for installing a roundabout was to help improve safety and reduce delay. Many agencies did state that roundabouts were chosen instead of all-way stop controlled intersections, because of the “undue delay” that all-way stop controlled intersections cause. It is believed that the respondents were referring to undue delay as the requirement of stopping for every vehicle at all-way stop controlled intersections versus the nearly continuous movement of vehicles at roundabout approaches.

Why should roundabouts be installed?

Many studies conducted in other countries have found that roundabouts help reduce accidents and also reduce delay. Roundabouts have unique geometric characteristics that promote the reduction in accidents and accident severity. For example, a traditional two-way or all-way stop controlled or signalized intersection has as many as thirty-two conflict or potential accident

points, while a roundabout has only eight conflict or potential accident points. This reduction in potential conflict points helps roundabouts reduce the frequency of accidents. In addition, the type of accidents that can occur at roundabouts do not include accidents such as right angle or left-turn head, which are normally severe accidents. This characteristic also helps to reduce the number of injury and fatal accidents that occur at roundabouts versus traditionally controlled intersections.

The reduction in delay is primarily attributable to the elimination of left turn delay which normally occurs at traditionally controlled intersections. As a rule, the left turning movement at signalized or stop controlled intersections are the most difficult for drivers to make due to the need to cross opposing traffic streams to complete the movement. Due to this, left turning traffic generally suffers the longest delays. In roundabouts, however, all entering drivers need only scan one direction of traffic for an available gap in the circulating stream, regardless of their desired movement.

The question that needs to be resolved for the U.S. is do roundabouts function as well here as they do in other countries. Can roundabouts be used in place of TWSC or AWSC intersections or perhaps signals? If so, what are the thresholds for determining their proper placement in the U.S.? For this study the use of roundabouts in lieu of TWSC intersections was studied.

Study Objectives

Several single lane roundabouts located in the States of Florida and Maryland were studied to

determine the effectiveness of roundabout installation in the United States. The purpose of this paper is to present the findings of the study which reviewed the safety and operational performance of roundabouts located in the U.S. Accident frequencies and rates were calculated for the study sites before and after the installation of the roundabouts. In addition, delay data before and after the installation of the roundabouts were collected and are presented. Also a comparison of field control delay to model delay is presented. Finally, preliminary findings regarding the estimation of single lane roundabout capacity are presented.

LITERATURE REVIEW

Safety Studies

While safety studies of roundabouts in the U.S. have been limited, many international safety studies have been conducted at roundabouts that were converted from traditionally controlled intersections. For example, a large study was conducted in Victoria, Australia on 73 roundabouts before and after their installation (3). Control in the before period included “Give Way to the Right”, “Stop” or “Give Way” and in one case police control. The findings of the study included a 74 percent reduction in the casualty accident rate after roundabouts were installed. Also, there was a 32 percent reduction in property damage accidents, although the authors point out that not all property damage accidents are reported therefore it is difficult to quantify the effects of the roundabouts on these types of accidents. In addition, there was a 68 percent reduction in pedestrian casualty accidents per year after installation of the roundabouts. Due to the low frequency of pedestrian accidents, however, this reduction was not found to be statistically

significant at the 10 percent level.

Van Minnen also conducted a study on roundabout safety in the Netherlands (4) . Van Minnen found that of 46 retro-fitted roundabouts, the casualty rate per year for the roundabouts reduced by 1.47 casualties/intersection/year. The casualty rate of cyclists and moped riders also reduced by 0.52 casualties/intersection/year or 74 percent. It should be noted that the before period of this study was longer than the after period. While the study's findings were encouraging and there were no reported fatalities on the roundabouts, in 1990 this all changed. In 1990, four fatalities involving cyclists riding along a marked bike lane within the circulating roadway, were reported. All of the accidents occurred when the cyclists basically ran into exiting trucks. Since the occurrence of these accidents, considerations are being made to eliminate the bike lanes within the circulating roadways. This findings should be utilized by American designers and engineers who are considering installing roundabouts in areas that have heavy bicycle traffic.

Delay Studies

Despite the fact that many roundabouts have replaced stop-control and signalized intersections around the world, few reports have been published regarding the reduction or increase in delay as a result of their installation. One study was conducted in Sweden, however, on a multi-lane roundabout that was used to replace a signalized intersection in December 1989 (5). The intersection had an average daily traffic of 12,480 vehicles. Queue and service time delay were collected in the before period by video taping at the site. Delay data in the after period were

predicted using a simulation model developed by the researchers. The findings of the study included a reduction in queue delay from 7.2 to 1.3 seconds/vehicle. Also the service time was reduced from 18.1 to 0.53 seconds/vehicle.

SAFETY PERFORMANCE OF ROUNDABOUTS IN THE U.S.

Study Sites

A safety study was conducted on five single lane roundabouts in the U.S. These roundabouts all conform to the standards of roundabout design such as yield on entry, deflection on entry and not allowing parking on the approaches or pedestrian traffic through the inscribed diameter. The sites range in average daily traffic from 7,600 vpd to 17,500 vpd. The sites chosen for this study and their peak hour and average daily traffic volumes are presented in table 1.

Accident data were assembled for these sites from accident reports provided by the respective local agencies. Prior to installation of roundabouts at all of the sites, the intersections operated as two-way stop controlled intersections with the exception of Fort Walton Beach, FL and Tallahassee, FL. These two sites are 3-legged intersections, therefore in their before period they operated as T-intersections.

Location	Date of Construction	Control Before Roundabout	Average Daily Traffic All Approaches	Peak Hour Volume All Approaches
Palm Beach County, Florida	November 1994	2-way stop control	7,600 vpd	510 vph
Lisbon, Maryland	April 1993	2-way stop control	8,500 vpd	856 vph
Tallahassee, Florida	August 1994	1-way stop control (T-intersection)	17,825 vpd	1,085 vph
Fort Walton Beach, Florida	May 1994	1-way stop control (T-intersection)	12,000 vpd	1,245 vph
Lothian, Maryland	October 1995	2-way stop control	15,000 vpd	1,345 vph

TABLE 1 Study Site Characteristics

Accident Data

Accident data were collected from hard-copy accident reports provided by the roundabouts' respective agencies. For each of the sites, with the exception of Lothian, Maryland, two years of before and after accident data were available. Lothian, Maryland was constructed in October 1995, therefore only one year of accident data were available for this site. The accident data before and after installation of the roundabouts, as provided by the accident reports are presented in table 2.

As shown in table 2, all of the sites, with the exception of Palm Beach County, Florida, saw a reduction in accident frequency after the installation of the roundabouts. To determine if the change in mean accident frequency was statistically significant, a one-sample t-test was conducted at the 95% confidence level. The null and alternative hypothesis and resulting

t-critical and t-statistical for the accident frequency is as follows:

$$H_0: \mu_A - \mu_B = 0$$

$$H_A: \mu_A - \mu_B \neq 0$$

$$t\text{-calculated} = 3.29 \quad t\text{-table} = 2.132$$

$$\text{degrees of freedom} = 4 \quad p\text{-value} = 0.030$$

$t\text{-calculated} > t\text{-table}$; therefore reject H_0 , and conclude

the before and after frequencies appear not to be the same at the 95% confidence level.

The accident rates for each of the study sites were also calculated and are presented in table 3.

Location	Accident Frequency/Year Before Period	Accident Frequency/Year After Period
Palm Beach Co., Florida	1.5	2
Lisbon, Maryland	7.5	2.5
Tallahassee, Florida	4.5	1.5
Ft. Walton Beach, Florida	8	2
Lothian, Maryland	13	4

TABLE 2 Accident Frequency Data

Location	Accident Rate per Million Entering Vehicles per Intersection per Year Before Installation of Roundabout	Accident Rate per Million Entering Vehicles per Intersection per Year After Installation of Roundabout
Palm Beach Co., Florida	0.56	0.71
Lisbon, Maryland	2.59	0.81
Tallahassee, Florida	0.71	0.22
Ft. Walton Beach, Florida	2.05	0.49
Lothian, Maryland	2.14	0.63

TABLE 3 Accident Rate Data

The accident rates for the study sites were calculated using the procedure presented in the Highway Safety Improvement Program Guide (6). Again, the change in mean accident rate for all the sites before and after the installation of the roundabouts was tested for statistical significance using a one-sample t-test. The null and alternative hypothesis and resulting t-critical and t-statistical for the accident frequency is as follows:

$$H_0: \mu_A - \mu_B = 0$$

$$H_A: \mu_A - \mu_B \neq 0$$

$$t\text{-calculated} = 2.80 \quad t\text{-table} = 2.132$$

$$\text{degrees of freedom} = 4 \quad p\text{-value} = 0.049$$

$t\text{-calculated} > t\text{-table}$; therefore reject H_0 , and conclude

the before and after frequencies appear not to be the same at the 95% confidence level.

Finally, injury and fatality data for the study sites were collected from the accident reports. Collectively the study sites experienced twenty injury accidents in the before period, including one right-angle fatal accident at the Palm Beach County site. After installation of roundabouts at the study sites, only one injury accident has occurred for the study period. This one minor injury accident occurred at Lothian, Maryland as a result of a rear-end accident on the approach roadway.

Based on the findings of the accident frequency, rate and injury studies, it can be demonstrated that U.S. roundabouts appear to be functionally as well as foreign roundabouts in terms of safety performance. Considering the limited experience that U.S. drivers have had with roundabouts, this is an encouraging finding.

OPERATIONAL PERFORMANCE OF ROUNDABOUTS IN THE U.S.

Study Sites

The same five single lane roundabouts studied for safety performance were also examined for operational performance. As previously mentioned, all of the sites were stop-controlled before the installation of the roundabouts. In addition, three of the sites were four leg intersections that operated as two-way stop controlled (TWSC) intersections prior to roundabout installation. The remaining two sites were three leg intersections that had stop-control on one approach in the before period.

Analysis Procedure

Two studies were conducted to determine the operational performance of the study sites. Part A of the study is a comparison of the study sites' average delay before and after the installation of the roundabouts; and Part B of the study is a comparison of the field measured delay to the analytical based software package SIDRA.

Part A

Control delay was estimated for the sites before and after installation of the roundabouts to determine the operational performance of the study sites. Control delay for the roundabouts was collected by video taping each of the roundabouts during their peak periods. Video cameras were placed on each of the approaches and control delay was extracted using a video editing deck in the laboratory. Control delay was determined for each entering vehicle at each of the sites. Control delay for this study is defined as the time spent in queue, move-up time in the queue and service time at the head of the queue. This definition was originally used in the 1997 Highway Capacity Manual update but has recently undergone a change. At the mid-year meeting in Portland, Oregon July 23-26, 1997 a resolution was passed to also include the deceleration time and acceleration time of a vehicle to their control delay. The deceleration time is the time spent decelerating before joining the back of the queue and the acceleration time is the time required to accelerate a vehicle to its cruising speed. The original definition of control delay was used to determine control delay for each entering vehicle by first determining the ideal travel time from

the video camera location to the yield bar of the roundabout. An ideal travel time would occur when an entering vehicle would proceed into the roundabout without interference of an existing queue of vehicles on the approach and immediately enter the circulating roadway without having to yield to circulating vehicles. The ideal time included the deceleration time due to geometric and operational changes in the roadway and also the acceleration time into the circulating stream. Once a mean ideal time was determined for each of the approaches of a site through a sample size 30 for each approach, each entering vehicle's travel time (from the video camera into the circulating stream) was recorded. This travel time included deceleration time; queue and move-up time in the queue; service time at the head of the queue and acceleration time into the circulating stream. To establish control delay, the ideal time for the appropriate entry was subtracted from each vehicle's recorded travel time.

Field measurements of the control delay for each of the sites in the before period, when stop controlled, were not available. Instead, an estimate of the control delay in the before period for each of the approaches and for each of the sites was made by using the procedure outlined in the 1997 update to Chapter 10 of the Highway Capacity Manual (7). An ideal comparison would be to have collected actual field control delay in the before period and compare it to the control delay collected in the after period. Unfortunately, this data was not available and instead an estimation had to be made using the HCM 1997 procedure. The comparison of the estimated control delay in the before period when the sites were stop controlled and the control delay for the same volumes flowing through their existing control of a roundabout is presented in table 4.

Location	Estimated Average Control Delay in Before Period (stop controlled) (sec/veh)	Measured Average Control Delay in After Period (roundabout) (sec/veh)
Palm Beach Co., Florida	2.71	0.97
Lisbon, Maryland	10.36	1.62
Tallahassee, Florida	5.58	9.04
Ft. Walton Beach, Florida	163.52	3.36
Lothian, Maryland	9.62	4.15

TABLE 4 Before and After Installation of Roundabout Control Delay

Overall the reduction in control delay was consistent for all with the exception of the Tallahassee site which was estimated to actually have seen an increase in control delay with the installation of the roundabout. The reason for this appears to be a reduction in delay for one approach from approximately 15 sec/veh and zero delay on the other two approaches, to a more uniform delay for all entering drivers. The benefits of roundabouts in reducing delay is clearly demonstrated in the Ft. Walton Beach site, in which control delay was reduced on average from 163.52 sec/veh to only 3.36 sec/veh. The large delay in the before period is primarily due to a significant left turning movement from the minor approach. In the before period this movement was estimated to have experienced control delay of nearly 320 sec/veh, while in the after period, it experienced on average control delay of only 4.41 sec/veh. The one known benefit of roundabouts is to help reduce delay to minor left turning movements as is demonstrated at the Ft. Walton Beach site.

This comparison demonstrates the benefits of roundabouts in terms of control delay reduction, as compared to TWSC or stop controlled T-intersections.

Part B

A comparison of the field measured control delay to a software package was also conducted. The purpose of this exercise was to determine the accuracy of this popular foreign analytical model to predicting delay at U.S. roundabouts. The field measured control delay for each of the sites' approaches was first compared to the predicted delay from SIDRA (Signalized and unsignalized Intersection Design and Research Aid) (8). SIDRA is a popular software package that is used by many agencies in the U.S. to not only analyze existing roundabouts but to aid them in decision making for future roundabouts. SIDRA determines measures of performance through an iterative process based on gap acceptance principles.

The procedure for estimating operational performance of roundabouts in SIDRA is based on gap acceptance theory. Generally, roundabout analysis models are either based on gap acceptance theory or empirical regression techniques. Empirical regression techniques require congested roundabouts to calibrate the models to predict capacity of entries. Gap acceptance models can be developed from field data collected at uncongested conditions. The predicted delay from SIDRA along with the actual delay measured in the field are presented in figure 4.

When comparing field measured delay to that predicted by SIDRA, it appears that SIDRA is fairly accurate. SIDRA appears to predict delay very well at low volume sites such as Lisbon or Palm Beach County. However, in the higher volume sites, Tallahassee, Ft. Walton Beach and Lothian, SIDRA tends to underestimate delay. A possible reason for this may be the difference in drivers between Australia (where SIDRA was developed) and the U.S. Perhaps U.S. drivers do not feel as comfortable as Australian drivers at higher volume sites.

Capacity of U.S. Roundabouts

The HCM is currently undergoing an update due to be published in early 1998. This update to the manual includes a procedure for estimating the capacity of single lane roundabouts (Chapter 10). While there are few single lane or multi-lane roundabouts in the U.S., an attempt has been made to test the accuracy of the capacity model for roundabouts based on field measured capacity. The HCM 1997 update contains the following equation to estimate approach capacity:

$$c_a = \frac{v_c e^{\frac{-v_c t_c}{3600}}}{1 - e^{\frac{-v_c t_f}{3600}}} \quad (\text{Eqn 0..Equation 1})$$

where: c_a = approach capacity c_c = conflicting circulating traffic

t_c = critical gap t_f = follow-up time (7)

One method for verifying the accuracy of this model is to observe an approach of a roundabout for a specific amount of time during which time the approach experiences continuous queuing and measure the flow of entering vehicles over that specific time period. In the U.S., this situation is difficult to find and may not exist at all. Single lane roundabouts in the U.S. have been installed in areas where volumes are typically low to medium. Due to this limitation, a procedure to estimate the potential capacity of single lane roundabouts has been developed. The procedure involved collecting each time headway in the circulating stream opposite the subject entry. Equation 2 was used to determine how many vehicles could feasibly fit into the measured available gaps in the circulating stream.

$$\frac{\text{Circulating stream headway} - \text{Critical gap}}{\text{Follow-up time}} = \frac{\text{Number of entering vehicles}}{\text{Equation 2}}$$

Critical gap is defined as the minimum gap that all entering drivers of similar locations will accept, assuming all entering drivers are consistent and homogeneous (9). Follow-on time refers to the time distance between two successive entering vehicles, utilizing the same gap in the priority stream. This information was collected for each approach at each site for an hour during the AM and PM peak periods. To calculate the estimated potential capacity for an hour, the individual results from equation 2 were summed over each hour of data collection. The values for critical gap and follow-up time were varied depending on if the desired result was field measured potential capacity, or predicted capacity as per the recommended HCM values of critical gap and follow-up time. The HCM procedure gives values for critical gap and follow-up

time in two ranges, specifically, upper and lower bounds as shown in table 5 that should be used if field data is not available

	Critical gap (sec)	Follow-up time (sec)
Upper bound solution	4.1	2.6
Lower bound solution	4.6	3.1

Table 5 1997 Highway Capacity Manual Values for Critical Gap and
Follow-up Times at Single Lane Roundabouts

Critical gap and follow-up time data have previously been collected for each of the approaches at each of the study sites by the Flannery (10). The procedure used to determine these data can be found in reference 10 but for clarity sake it is noted here that the maximum likelihood technique was utilized to determine critical gaps.

Figures 5,6 and 7 demonstrate the accuracy of the HCM procedure as compared to potential capacity measured at 22 approaches of single lane roundabouts. The data were collected over a total of 42 hours resulting in 42 field potential capacity data points. From figure 5 it appears that the HCM procedure is fairly accurate at predicting capacity as compared to field measured capacity, especially at lower volume sites. Figures 6 and 7 utilize the recommended values for critical gap and follow-up time as per the HCM procedure. These figures do not show any particular trend of either over or under predicting capacity and there appears to be a good representation of accurate measurements. Further investigation is currently underway to

determine if there are any unreported characteristics, such as site geometry, which may be causing the inaccuracy in the HCM procedure prediction of capacity.

FINDINGS AND RECOMMENDATIONS

This study was conducted to evaluate the safety and operational performance of single lane roundabouts in the U.S. The study showed that roundabouts have been used successfully in two states to help reduce accident rates and frequencies and also to help reduce control delay. In addition, a popular foreign method of determining delay for roundabouts was utilized to estimate delay for the same five single lane roundabouts. A comparison of the field measured delay and the predicted delay of the model was also presented and it appears that SIDRA can accurately predict delay for American single lane roundabouts. Finally, findings regarding the accuracy of the 1997 HCM procedure for estimating capacity of roundabout approaches were discussed. At present, based on a small sample size, it appears that the HCM model for estimating capacity may be too optimistic. However, it should be noted that the measured capacity is potential capacity and not actual capacity due to the lack of congested single lane roundabouts in the U.S. Further studies need to be conducted to compare potential capacity to actual capacity.

Recommendations that can be made based on this study include consideration be given to roundabouts as an alternative to TWSC intersections in terms of improving safety performance. In addition, the use of SIDRA to predict delay, in lieu of an American delay model, appears to be valid. SIDRA was found to accurately predict delay at low volume sites in the U.S. A delay

prediction model for roundabout approaches is currently being developed based on U.S. conditions by the authors.

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Figure 1 Yield on Entry at Roundabout Located in Lothian, Maryland



Figure 2 Deflection on Roundabout Entry in Ft. Walton Beach, Florida



Figure 3 Flared Approach in Vail, Colorado

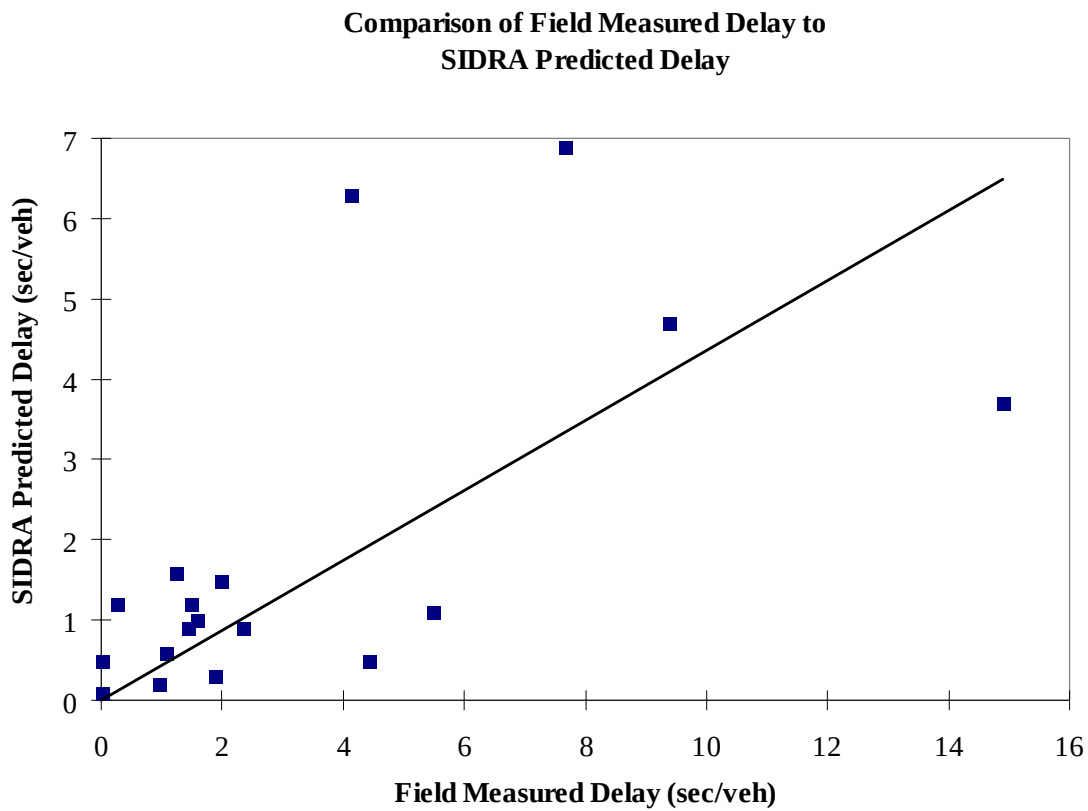


FIGURE 4 Comparison of Field Measured Delay to SIDRA Predicted Delay

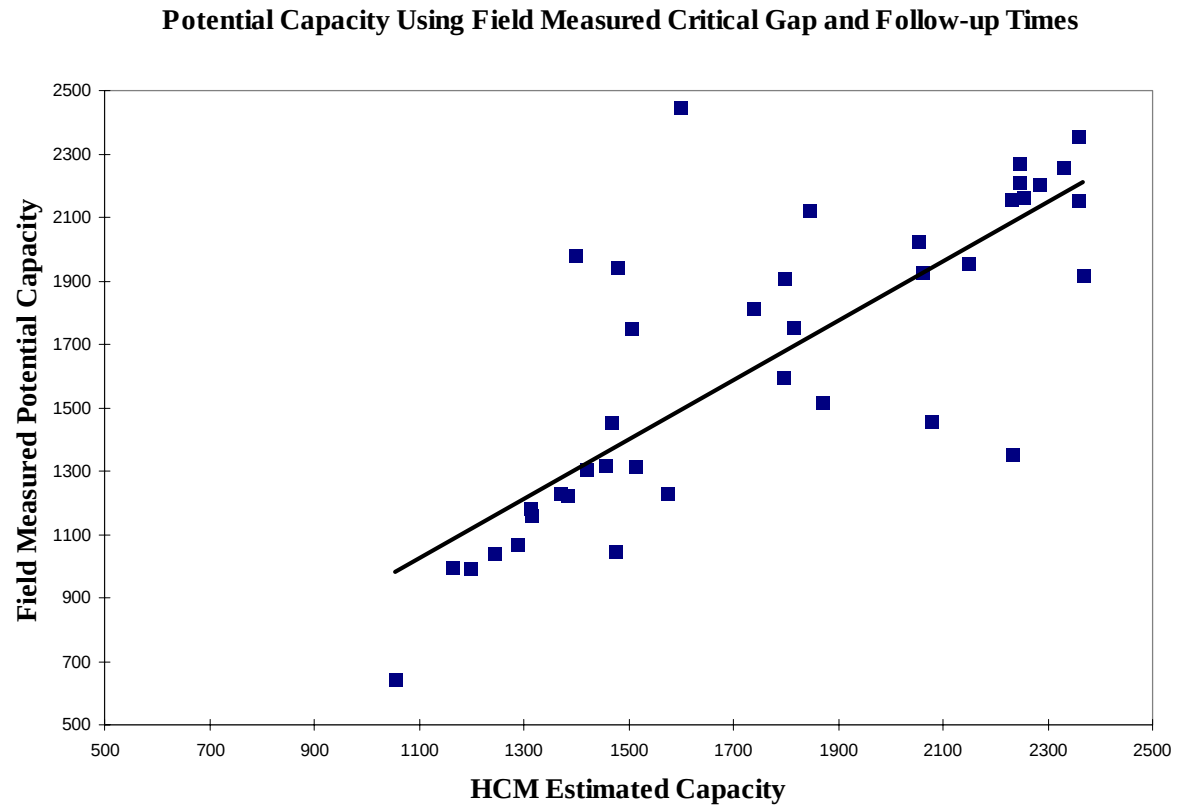


FIGURE 5 Comparison of HCM Estimated Capacity and Field Measured Potential Capacity

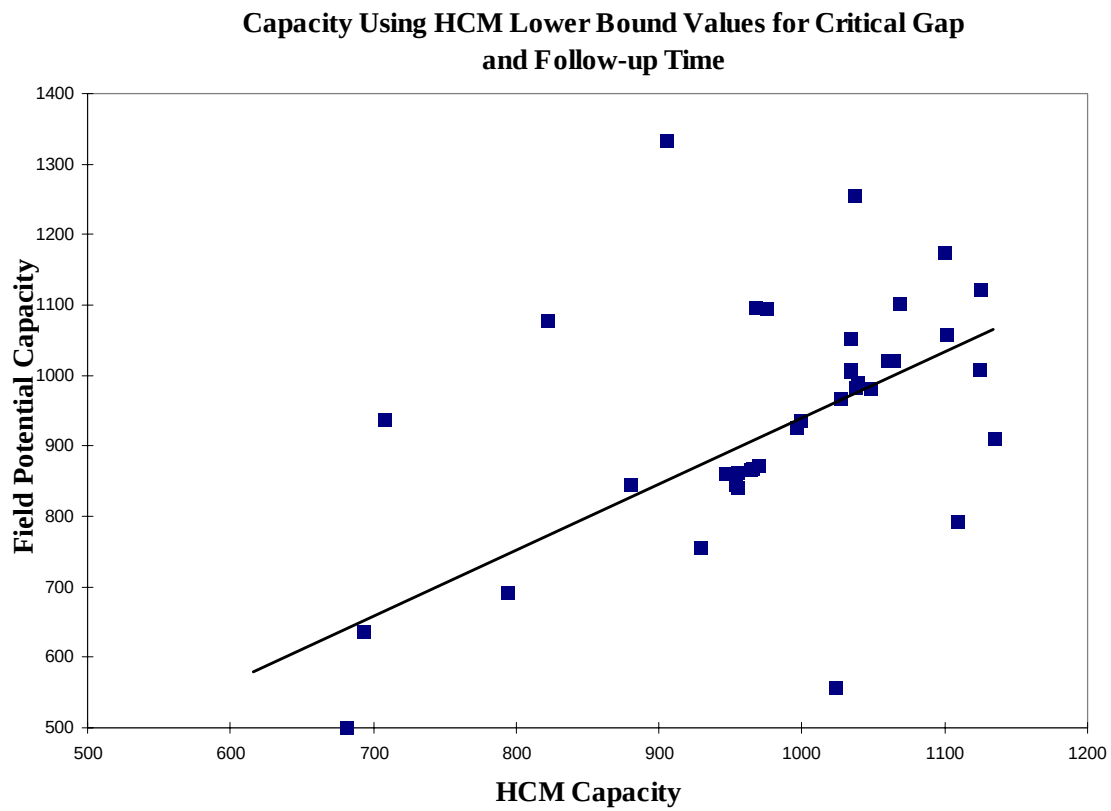


FIGURE 6 Comparison of HCM Estimated Capacity and Potential Capacity Using HCM Lower Bounds

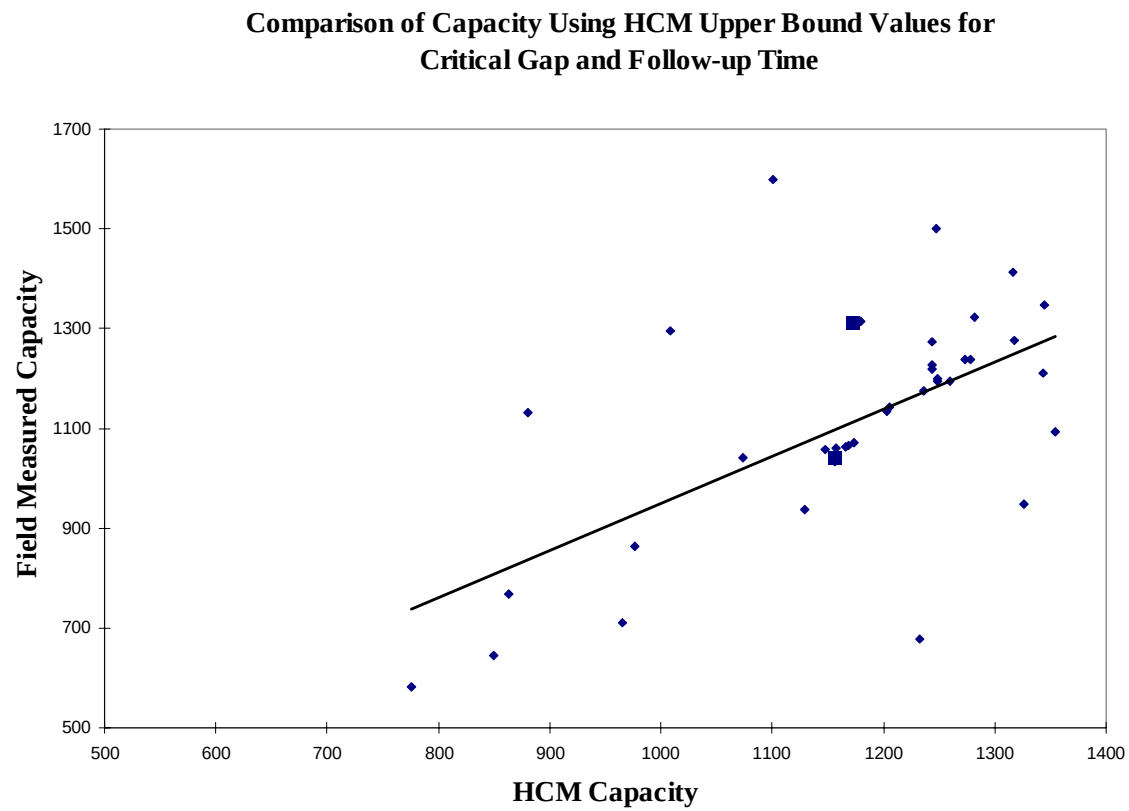


FIGURE 7 Comparison of HCM Estimated Capacity and Potential Capacity Using HCM Upper Bound