DCT 199

Use of Roundabouts as Alternatives to All-Way Stop Controls

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Roundabouts

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EXECUTIVE SUMMARY

This report evaluates the performance of modern roundabouts in Delaware. Delaware Department of Transportation is planning to install modern roundabouts to replace some other types of intersection control. The primary purpose of this report is to obtain Delaware-specific parameters for design of the modern roundabout such as the critical headway and follow-up headway. Three modern roundabouts in Delaware and two in Maryland were the basis of this study. Maryland is one of the leading states in the use of modern roundabouts in the United States. The roundabouts in Maryland were included to enable some comparisons to be made between the critical headway and follow-up headway obtained from each state. Comparing the parameters obtained in Maryland to a similar research carried out in summer of 2005, it became apparent that the critical headway had reduced. While a statistically rigorous approach was not used a decrease in critical headway significantly impacts the performance of the roundabout. The capacity increases and queue lengths and delay will decrease. It stands to reason that as drivers get more and more comfortable driving the roundabouts, they will accept smaller but safe gaps to merge into the roundabout thus reducing the critical headway.

Computer simulations were used to assess the capacity (v/c ratios), delay, and queue lengths. The simulations were based on HCM, aaSIDRA, and the NCHRP approach described in Report 572. Preliminary results indicated that the roundabouts are performing at an acceptable level of service. The capacity at Rehoboth however is exceeded leading to long queue lengths and delays from the simulation. This is the result based on the volumes generated with Delaware Department of Transportation (DelDOT) Penninsula Model. No significant delays or queuing were observed at the site during data collection.

Crash analysis was conducted based on incidents reported before construction of the roundabout and after construction where appropriate. Sufficient data is not available to make sound conclusions on safety. As time elapses sufficient post roundabout data can be collected for a statistically accurate estimate.

There was virtually no pedestrian activity at all the locations studied except Rehoboth. Vehicle-pedestrian (and bicyclist) observations did not reveal any alarming issues. No excessive delays imposed by one group on the other were observed. Motorists yielded as needed. A few pedestrians at this location were not using the crosswalks provided to cross the streets. A few crossings were being initiated at the yield line which imposed further delay on motorist waiting to merge. No audible pedestrian signals (APS) were on site to assist any blind pedestrians that may cross the streets at this location. It appears there is a push to make this provision mandatory and future roundabouts may have to provide APS.

These observations from this research will enhance the planning and design of roundabouts in Delaware. Continued research will enable a more complete and reliable assessment of modern roundabouts in the state.

1 INTRODUCTION

1.1 Problem Statement

Modern roundabouts have been used successfully in many parts of the world such as UK, France and Australia to control traffic at intersections. Even though relatively new to the United States, modern roundabouts are gaining popularity as an intersection treatment for improving operational efficiency and vehicle safety. When properly designed, a modern roundabout is superior in safety and can handle higher volume of traffic with less delay compared to a signalized or all-way-stop control intersection. For these and many other reasons modern roundabouts have generated a lot of interest over the past few years in the United States and more transportation agencies have considered them for implementation.

The Delaware Department of Transportation (DelDOT) has implemented a few modern roundabouts in the state and intends to convert many other intersections to operate as modern roundabouts. In view of the novelty of the modern roundabout to the planners, design engineers and the general public, was deemed appropriate to assess the performance of modern roundabouts on the highway system in Delaware. This assessment after implementation of a few modern roundabouts in the state will yield information that will give more insight into its use in Delaware. The need for this research was underscored by problems that arose in Middletown, Delaware, where heavy vehicles were having problems going through a modern roundabout that was installed at the intersection of Bunker Hill Road and Choptank Road. At this location it appears the modern roundabout designed and constructed was not adequately sized and therefore large vehicles were having problems going through this location. The goal of this research therefore is to assess the performance of some selected modern roundabouts in operation in Delaware and make recommendations to enhance operation.

1.2 Objectives

Delaware Department of Transportation is in the process of planning and designing many more roundabouts in the state. The primary objective of this project is to assess the performance of the few roundabouts that have already been constructed in Delaware, and to make recommendations to improve future installations in the state. This will be done by carrying out field observations to determine the following parameters at each site:

- Critical Headway
- Follow-Up Headway
- Delay and Queue Lengths
- Driver, Pedestrian and Bicyclist Behavior

The observations will be used in quantitative analysis to determine the critical head way, follow-up headway, delay and queue lengths. Also pedestrians, bicyclists and driver interactions at roundabouts will be observed for safety assessments and recommendations. This current work will defer research on relationship between geometric characteristics of the modern roundabout on safety and performance for all users. Due to the limited number of roundabouts constructed in the state, state specific parameters may be more challenging to obtain.

1.3 Organization of Report

Chapter 1 is the introduction of the report and discusses the problem statement and objectives of the research. Chapter 2 gives a brief literature review to provide a context for the research that was performed. It highlights some facts about roundabouts and distinguishes the modern roundabout from traffic circles which were used in the past in the United States. Chapter 3 describes the methodology and the equipments that were used in this research. It highlights some of the limitations posed by the available equipment and how the researchers worked around these limitations. Chapter 4 discusses the data collected and the analysis done to extract various quantitative parameters. These parameters include critical gap, follow-up headway, delay and 95th percentile queue lengths and level of service. The entry capacities of the entry leg and the intersections are evaluated. This chapter also discusses driver, pedestrian, and bicyclist interaction approaching the modern roundabout. Chapter 5 gives some recommendations to improve the operational performance of modern roundabouts in Delaware and what needs to be done in future research.

2 LITERATURE REVIEW

2.1 History of Modern Roundabouts

Roundabouts have been used in many countries to control traffic at intersections for several decades. Roundabouts became popular and successful because of the reduction in accidents leading to injury, reduction in traffic delays, improvement in fuel consumption, less air pollution, and cheaper construction and maintenance cost [1].

The modern roundabout has evolved from traffic circles and rotaries that were built in the first half of the 20^{th} century [2]. Even though rotary systems existed, 1903 became a pivotal year in the transition to roundabout as we know it today since that was the time one way rotary system was proposed. The rotary system prior to this time allowed two-way circulation of traffic until the one-way circulation was implemented in 1904 at Columbus Circle in New York City by William Phelps Eno. At that time the central islands were relatively small, about 5 ft wide, until bigger islands were proposed in 1906 for the city of Paris by Eugene Henard.

Roundabouts have gone through many changes in design and operation from the initial traffic circles to the current modern roundabout. The operation of this intersection control with regard to who has the right-of-way varied from location to location in the US. While in some parts the major thoroughfare had the right-of-way, other areas adopted the “first-in” rule. In 1913 Wisconsin became the first to adopt the yield-to-right rule. Vehicles in the circulating lane were required to give way to merging traffic usually coming in at high speed. This rule allowed high speed merging and weaving which led to designs with large radii also known as the traffic circles.

This operational approach led to unsafe situations because of the high speed merge as well as gridlocks when the circulating traffic stopped. In the mid-1960s Britain changed this operational concept and adopted the “offside priority rule” at roundabouts [3]. The rule required all entering vehicles to give right of way to traffic already in the circulating lane. Merging traffic was required to wait and use a gap in the circulating stream to merge into the circle. This new operational principle led to an increase in capacity and therefore in 1966 Britain officially adopted this for the operation of the roundabout. This yield-at-entry coupled with other changes such as deflection around the central island and flaring of the approach marked the genesis of the modern roundabout. The word “roundabout” was coined by the British who have since used this form of intersection control extensively on their road network.

The modern roundabout has been used successfully as an intersection control in many parts of the world including Australia, France, Germany and Switzerland. Its use in the US was limited until recently when it became popular. Use of the roundabout was limited because many transportation professionals and agencies were hesitant to install roundabouts since they had limited knowledge of its performance under local US conditions. The few agencies that implemented then had to rely on consultants with roundabout design experience using surrogate standards borrowed from other countries, or the local agencies had to develop their own set of standards. In order to address this problem and to provide a policy for design consistent with safety and driver expectation in the United States, the Federal Highway Administration (FHWA) developed the document, *Roundabouts: An Informational Guide.* Other documents have been published such as the NCHRP Report 572 with extensive information to aid planners and engineers use roundabouts effectively.

The first two modern roundabouts in the United States were constructed in Summerlin, Nevada in 1990 [4]. In recent times the modern roundabout has gained traction and has been used by transportation professionals as an alternative to other intersection controls with very favorable results. This surge however has met with mixed feelings from a cross-section of the general public – pedestrians and motorists alike. The general public's sentiments about modern roundabouts range from those whose dislike stems from bad experiences with other circular intersections like rotaries and traffic circles, to others who embrace and advocate it as a better alternative to stop control or signalized intersections. One of the often sited issues with those with reservations about the use of the modern roundabout is that it is not friendly to people with vision impairments that depend on traffic cues to cross streets.

In spite of the challenges posed above some states, for instance Maryland, have used it extensively and many more states have started using the modern roundabout on their roadway systems. For instance Ohio Department of Transportation requires all personnel involved in project planning, scoping and development to at least consider other intersection control alternatives besides traffic signals. This means that the feasibility of a modern roundabout must be explicitly considered. The state of Washington has over 120 roundabouts on the state highway system and some of these modern roundabouts replaced signalized intersections. Washington has also implemented a policy of not allowing traffic signals on roads with speeds greater than 45mph. Also states like Wisconsin, New York, Minnesota and others have adopted policies that require consideration of roundabouts as intersection controls before considering traffic signals. Kansas and Virginia have had success using roundabouts on rural roads. Oregon is experiencing much success and acceptance in various cities and counties that have implemented roundabouts. There is no doubt that the modern roundabout curries favor with some design engineers and more and more of these intersection controls will be seen on the road system in different parts of the United States. Anecdotal evidence shows that usually those who vehemently oppose the use of modern roundabouts become persuaded after the tangible benefits manifest themselves. The subsequent section will further discuss some of these benefits.

2.2 Benefits of Using Modern Roundabouts

The benefits that have been derived from using roundabouts as opposed to other intersection controls like all-way-stop or signalization are safety, improvement in performance, an enhancement in the aesthetic value to the community, and low maintenance cost. Roundabouts have also been installed to calm traffic, and in some instances used for urban revitalization. The environmental benefits of roundabouts cannot be discounted since fewer emissions from vehicles means a cleaner environment. However some of these benefits are not realized instantly. In a study [4] conducted by Shrestha et al in 2002, this research revealed that the full benefits of a modern roundabout are realized about 5 years after installation. The authors assert that the reasons are two-fold based on operational and economic factors. Operational factors are impacted because drivers, pedestrians and bikers must get familiar with it. Indicators of economic benefit also take time to manifest.

2.2.1 Improvement in Capacity and Delay

There are several reasons the modern roundabout is gaining popularity in many states across the US. Generally there is improvement in capacity and delay since vehicles keep moving when there is no conflicting vehicle. Stopping is the major cause of delay at intersections. Reduced stopping means fewer delays. Compared to a signalized intersection for instance, vehicles entering the intersection are required to stop on the yellow or red light whether there are vehicles on the other approach legs or not. In addition, each signal has an inevitable lost time when it cycles through the different phases. This lost time is never made available for motorists to use thus adding to the delay. Compared to a modern roundabout where all approach vehicles do not have to wait to merge into the roundabout if there is no conflicting vehicle. Also all approach or entry traffic at a modern roundabout can enter the intersection simultaneously [5]. This simultaneous merge is something unique to a modern roundabout. In suburban areas where side street traffic may be subject to long delays in the absence of signals, research [6] shows a roundabout may provide the needed entry capacity from a minor or secondary road onto the main road thus reducing delay.

2.2.2 Improvement in Safety

A well designed modern roundabout regulates the traffic flow very efficiently without the need for signals. It provides simplicity and consistency of operation since all vehicles always enter the intersection by making a right turn, which significantly reduces the number of conflict points. A roundabout has 8 conflict points compared to 32 conflict points at a signalized intersection. The fewer conflict points significantly reduce potential crashes. Figure 1 shows the conflicts points at a modern roundabout and a signalized intersection.

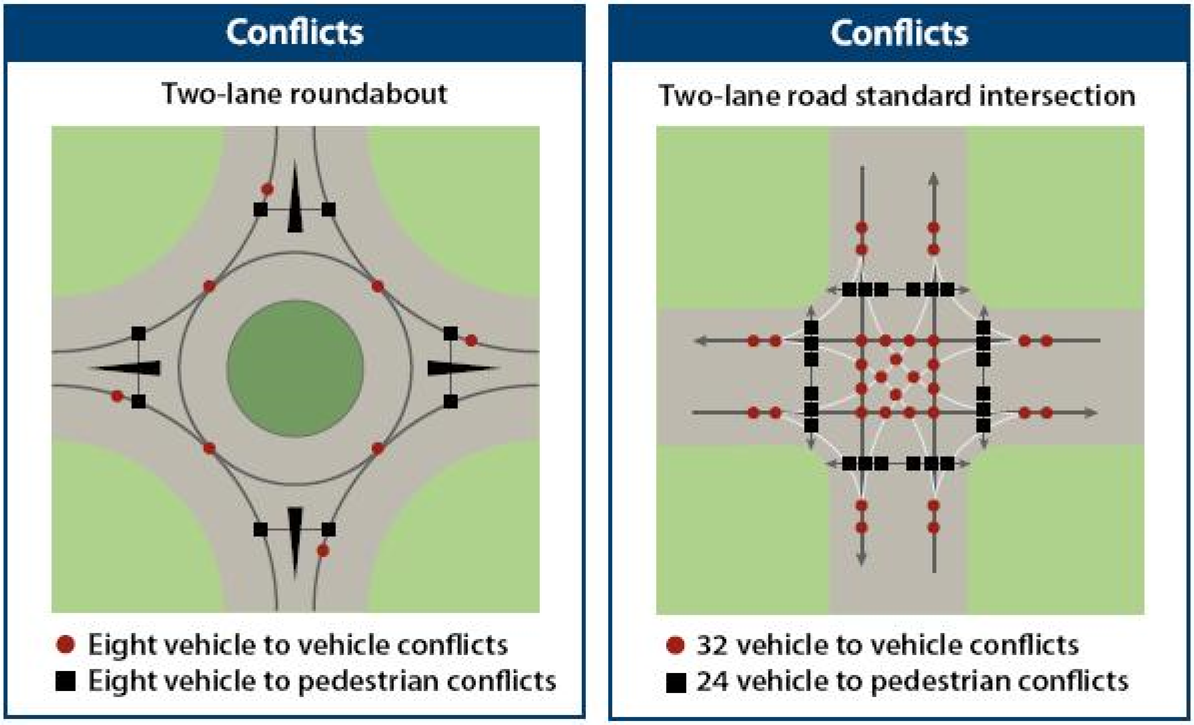

Figure 1 Vehicle conflict points at a roundabout and a signalized intersection [Source FHWA-SA-09-018]

Also the deflection provided at the entry point induces a calming effect on approaching drivers thus reducing speeds which directly reduces the severity of impacts. In the event of crashes, the most dangerous T-bone crashes are virtually eliminated since vehicles merge at low angles instead of perpendicular angles. A study done by the Insurance Institute for Highway Safety on signalized intersections that were converted to roundabouts showed that all crashes were reduced by 39%, crashes resulting in serious injuries were reduced by 76% and it is expected that fatalities will be reduced by 90% [7]. In the event of power outages, after maybe a severe storm, roundabouts continue to function flawlessly without posing any additional hazard at the intersection.

2.2.3 Environmental

A roundabout also improves the environmental quality in terms of emissions. Vehicles do not have to stop at the intersection if there are no conflicting vehicles. The continued flow eliminates excessive emissions associated with acceleration and deceleration of vehicles as well as noise pollution. Reduced stop delay at the intersection reduces idling time and for that matter the emissions that result from idling. This reduces pollutants from exhaust fumes and cost to motorist in terms of lost fuel.

2.2.4 Aesthetic

Roundabouts can improve the aesthetic appeal of a locale and so it has widespread support among planners and residents [2]. The central islands of roundabouts provide opportunities for landscaping or erection of monuments of cultural significance to a town. Usually the central island is beautified by residents and can serve as the gateway to a community.

2.2.5 Cost

The literature does not appear to be consistent on the initial cost of a roundabout. While some sources claim the initial cost is much higher than a signalized intersection, others also claim a roundabout costs less since it does not require expensive traffic signals and control boxes with their costly annual maintenance. Furthermore some literature claim that a roundabout will cost more for initial construction and also maintenance and protection of traffic during repaving, and also snow removal will also pose a challenge.

However there is consensus that the life cycle cost of a roundabout is by far cheaper than a signalized intersection. Also the safety that a roundabout affords, for instance reduction in fatalities is significant if safety is factored into the cost. The National Safety Council estimates the comprehensive cost of a fatality to be $4.2 million, and incapacitating injury to be over $400, 000. Roundabout reduces fatalities and injuries by 90% and 76% respectively.

2.3 Challenges for Modern Roundabouts

There are some locations where a roundabout will not be appropriate. These are: high traffic volume locations; locations with limited right-of-way; locations with very high pedestrian use and multilane approaches; intersections on grades. In a simulation study by Vlahos et al. [8] noted that the performance of roundabouts begins to decline at very high demand volumes and at a certain point signalized intersections become the preferred option.

2.4 Modern Roundabout vs. Traffic Circle

The modern roundabout is different from a traffic circle or rotary both in the geometric design and operational principle. Some of the differences given in [5] and [9] include the following:

- Modern roundabouts have smaller sizes than some traffic circles and are designed with a flare and deflection at the entry. Traffic circles may enter at the perpendicular angle.

- Modern roundabouts operate with a yield control at the entry whereas traffic circles may have a stop control or no control at the entry. At some locations where traffic circles are used, the circulating traffic is required to yield to traffic entering the circle.

- For modern roundabouts all traffic entering the circle circulates in an anti-clockwise direction, whereas in traffic circles left turning vehicles are not required to do so.

- The mode of operation at traffic circles sometimes leads to a gridlock. In modern roundabouts vehicles only enter the circle when there is an acceptable gap and this problem is eliminated.

- High speed merge at traffic circles made accidents more injury prone. On the other hand the modern roundabout has a calming effect on traffic and accidents are not as severe.

- Modern roundabouts do not permit pedestrian access into the central island and pedestrians are only allowed to cross at the legs behind the yield line. Parking is not permitted within the circulatory roadway either. Traffic circles may allow pedestrian access to island and parking in the circulating lane.

The adverse operational effects of traffic circles made them unpopular and the design for them has been discontinued. Some states are currently converting old traffic circles into modern roundabouts.

3 METHODOLOGY

3.1 Approach

The objective of this research is to assess the performance of roundabouts in the State of Delaware. The principle on which a modern roundabout operates is for a driver at the approach to use an acceptable headway in the circulating stream to merge into the circulating lane or else wait for one. Performance of the roundabout in terms of delay and queue lengths depends on the distribution of gaps in the circulating traffic and the gaps drivers on the approaches find comfortable to use to perform the maneuver. Therefore gap acceptance studies were carried out at each roundabout in order to make an estimate of the critical gap.

In order to carry out the gap acceptance studies, a video camera mounted on a tripod was used to videotape headways between the vehicles in the circulating lanes, and the gaps drivers at the approach used to merge into the circulating lane. If there is a queue and more than one driver uses the same gap in the circulating lane, the follow-up headway is also determined from the video data. Three sites in Delaware (Wilmington, Middletown, Rehoboth) each with a modern roundabout were selected for video data collection. Since an omni-directional video camera was not available, the researchers could only capture data at each entry. However in Wilmington, DE, there was a vantage point where the camcorder mounted on the tripod could capture all entry and exit approaches of the roundabout. The video camera was a standard digital camcorder with a counter clock. Headway data were extracted later in the laboratory by playing back the recorded videos. Geometric information of each roundabout was also obtained for each site.

The data was analyzed for the critical headway and follow up headway. The results obtained are also compared with work done by FHWA in NCHRP Report 572 and Highway Capacity Manual. This will enable a comparison of Delaware parameters to national parameters contained in these documents. Since Maryland is a neighboring state which has used more modern roundabouts, the results are also compared with two other roundabouts in Cecil County and Queen Anne's County, which are close to Delaware. Similar work [10] conducted by Vlahos (2006) gives us some historical data which became a basis to compare the results them to those obtained in this current work.

3.2 Limitations of Equipment

The software (PIXELA Image Mixer 3 SE Player Ver. 5) used did not permit conversion of the video into time frames that would have permitted a more precise measurement of arrival and departure times. The equipment used in the studies by Vlahos [10] did not encounter this problem. The time stamps were accurate to HH:MM:SS:FF, where FF are frames (30 frames per second). and the work is more precise in determining the gaps and follow-up times. The PIXELA software could not give this level of accuracy. However the speed of vehicles circulating in the roundabout is very low therefore the level of accuracy using the PIXELA equipment compare favorably with the work done in Vlahos [10].

Furthermore, the method chosen out of the three mentioned earlier to use in determining the headway has an impact on the obtained value [2]. The approach used in this work is similar to Method (1) described in NCHRP Report 572 [2], which is expected to have a shorter critical gap compared to other available methods. However this is the same method used in [10] and therefore valid comparisons can be made.

3.3 Computer Simulation

Computer simulations were used to determine parameters such as queue lengths, LOS, delay and the capacity of the modern roundabout. The software used are aaSIDRA (SIDRA) and Highway Capacity Software. A simple spreadsheet was used to evaluate these parameters also based on NCHRP 572 approah. SIDRA is approved by the Federal Highway Administration for roundabout analysis [9]. This software analyzes performance characteristics of roundabouts using empirical gap-acceptance method taking into account the geometry of the roundabout and driver behavior [10]. SIDRA allows calibration to better model driver behavior and also environmental factors. The roundabout analysis was carried out with the observed values of critical gap and follow-up time.

3.4 Site Selection

At the start of this project, there were only five modern roundabouts that were operating in the state: two in Wilmington, New Castle County; one in Middletown, New Castle County; one in Dover, Kent County; and one in Rehoboth, Sussex County. Three of these sites in Delaware were chosen for the study. In addition two other sites from Maryland were added to the study making a total of five sites. The two sites from Maryland were included because in 2005 a research study [10] yielded some results and the current work would attempt to capture any change that might have occurred. For instance the results obtained for critical gap and follow-up time in 2005 can be compared to those determined in June 2009 after a period of about four years. Figure 2 shows the location of these sites Table 1 gives geometric features of each of the roundabouts studied.

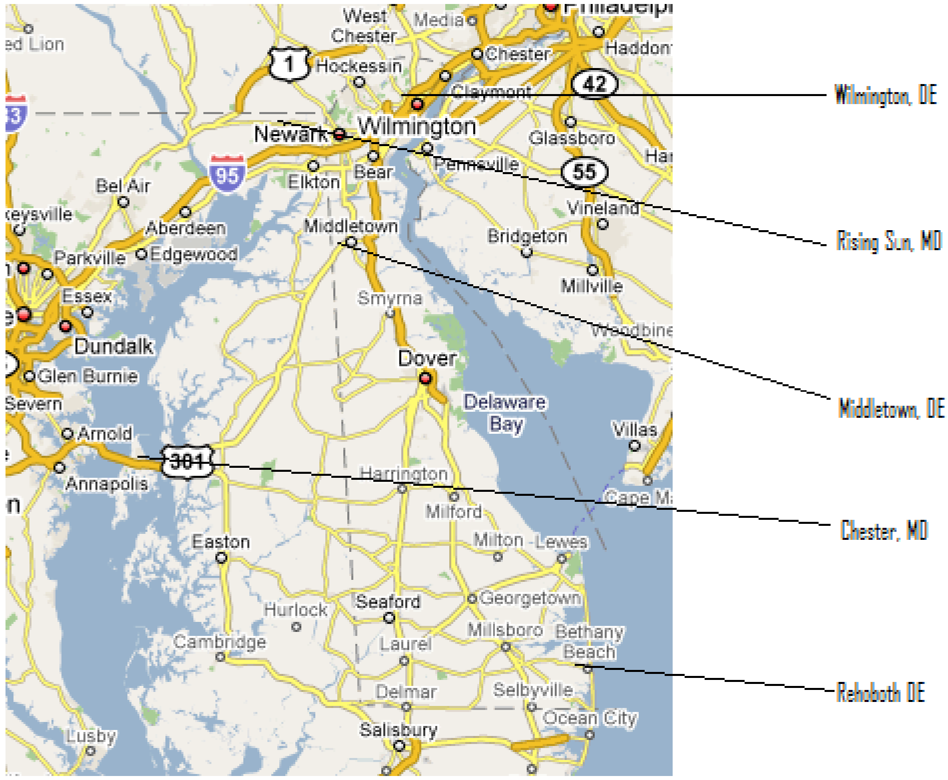

Figure 2 Location of study sites in Delaware and Maryland

3.5 Demographics of Chosen Sites

According to the US population census the 2006 estimate for the population of the city of Wilmington is 72,826 with 25.9% aged 18 years or over. The total households as noted in 2000 were 28,617. The mean travel time to work for workers 16 years and over is 22.9 minutes. Middletown has a population of 6,161 of which 4258 (69.1%) are of age 18 years and above and household population of 6152. For persons who are 18 years and older, the mean travel time to work is estimated at about 32.4 minutes. The population estimate for Rehoboth Beach City is 1587. Over 93% are 18 years or older and the mean travel time to work for workers 16 years and older is 20.3 minutes.

3.6 Data Collection

Critical gap and follow-up headway were two parameters this research wanted to estimate for each roundabout in the study. In order to do this a video camera mounted at a vantage point to record the entry and circulating lanes at each roundabout was set up. Figure 3 shows the setup used to collect traffic data. The use of a video camera is noteworthy because it permits the use of the minimum number of personnel and the video clips can be reviewed several times to obtain the most accurate information. Unlike an omni-directional camera that can record information on all approaches simultaneously, this set up allowed limited view of the roundabout i.e. an approach leg and part of the circulatory roadway. Video data can be used to manually extract information on volume, delay, speed and gaps and lags, however it is a tedious process. The video was used to determine the rejected gaps or lags and accepted gaps or lags of drivers entering the roundabout as well as the follow-up times in instances where there was a queue. Uncontested gaps – gaps that occurred while there was no entry vehicle waiting - were not used in this analysis.

Table 1 Geometric information for selected roundabouts

Location	Site Name	Geometric Parameters					Length of video (mins)
		Inscribed Circle Diameter (ft)	Island Diameter (ft)	Circulatory Lane Width (ft)	Apron Width (ft)	# Approach Legs	
Wilmington, DE	West Park Dr & East Park Dr	128	90	19	2	3	73
Middletown, DE	Bunker Hill & Choptank Rd	111	78	17	20	4	142
Rehoboth, DE	Rehoboth Ave & Grove St	136, 100	70	15, 33	10.4	4	147
Chester, MD	Castle Marina Rd & MD 18	110	50	18	12	4	70
Rising Sun MD	MD 273 & MD276	141	113	14	14	4	73

Figure 3 Camcorder mounted on tripod to videotape vehicles at roundabout

4 ANALYSIS

4.1 Critical Gap

At a modern roundabout, vehicles approaching the circle must yield right of way to vehicles already in the circulating lane. Vehicles at the entry leg can only enter the circle when there is an acceptable gap. Therefore the performance of a roundabout to a large extent depends on the gap acceptance behavior of drivers entering the circulating stream. The critical gap is the minimum headway acceptable to a driver to enter the roundabout. Generally the critical gap is dependent on the circulation flow, the size of the roundabout and the flows at the entry lanes. It is assumed that any headway smaller than the critical gap will be rejected by the driver; conversely the driver will accept a headway greater than the critical gap. It is assumed that such driver behavior will remain consistent however Mahmassani and Sheffi [11] surmise that under congested conditions, driver behavior changes and drivers will accept headways less than the critical gap. This assertion is not corroborated by the NCHRP Report 572 [12] since the field observation from that research did not show drivers in a queue accepting headways lower than the critical gap.

Research conducted by FHWA [12] highlights three different ways of determining the critical gap: (1) inclusion of all observations of gap acceptance, including accepted lags; (2) inclusion of only observations that include a rejected gap; (3) inclusion of only observations where queuing was observed during the entire minute the driver rejected a gap. The methodology used in method (1) above typically results in critical gaps that are shorter than critical gaps obtained using method (2). Besides the method used, the critical gap at any given location depends on local traffic conditions such as waiting time and driver behavior [13]. All the roundabouts where data was collected for this research were not heavily congested even though data was collected at peak travel times.

During data collection, it was apparent that some drivers were uncertain what to do approaching the roundabout. A few approach drivers did not yield to the circulating traffic forcing some drivers in the circulating lane to make evasive maneuvers. Also some drivers waited for considerably long gaps to merge. In other instances drivers in the circulating lane were yielding to drivers at the approach. This led to further delays for other users. It is apparent that as time goes on and drivers become familiar with the operation of the modern roundabout, merging will be much more fluid and this will lead to a reduction in the estimated critical gap. Table 2 provides a summary of the locations, sample size and some parameters of the data collected.

Table 2 Observed lags and gaps

Location	Sample Size		Mean (s)	
	Rejected	Accepted	Rejected	Accepted
Wilmington, DE	80	168	2.50	3.04
Middletown, DE	115	188	2.43	3.13
Rehoboth, DE	1113	421	2.09	2.76
Chester, MD	304	156	2.17	3.02
Rising Sun, MD	147	137	2.35	2.84

4.1.1 Wilmington, DE (West Park Drive and East Park Drive)

Field observations during data collection revealed flows that were fairly directional. In the mornings traffic headed east and in the evenings flow reversed and most of the traffic was heading west at the roundabout. These were mainly through traffic with few vehicles making turns. It appears the fairly directional nature of the movement resulted in fewer opportunities for to observe merging maneuvers and therefore the gap acceptance behavior of drivers. Table 3 shows a summary of data on the accepted and rejected gaps during the observation. Figure 4 shows the intersection of the two curves as the critical gap determined for the site.

Table 3 Data on gaps accepted or rejected by drivers at West Park Drive and East Park Drive, New Castle County

Time gap (s)	Period observed: AM & PM	
	Accepted number	Rejected number
1	17	0
2	30	45
3	19	83
4	8	30
5	4	9
6	1	1
7	0	0
8	1	0

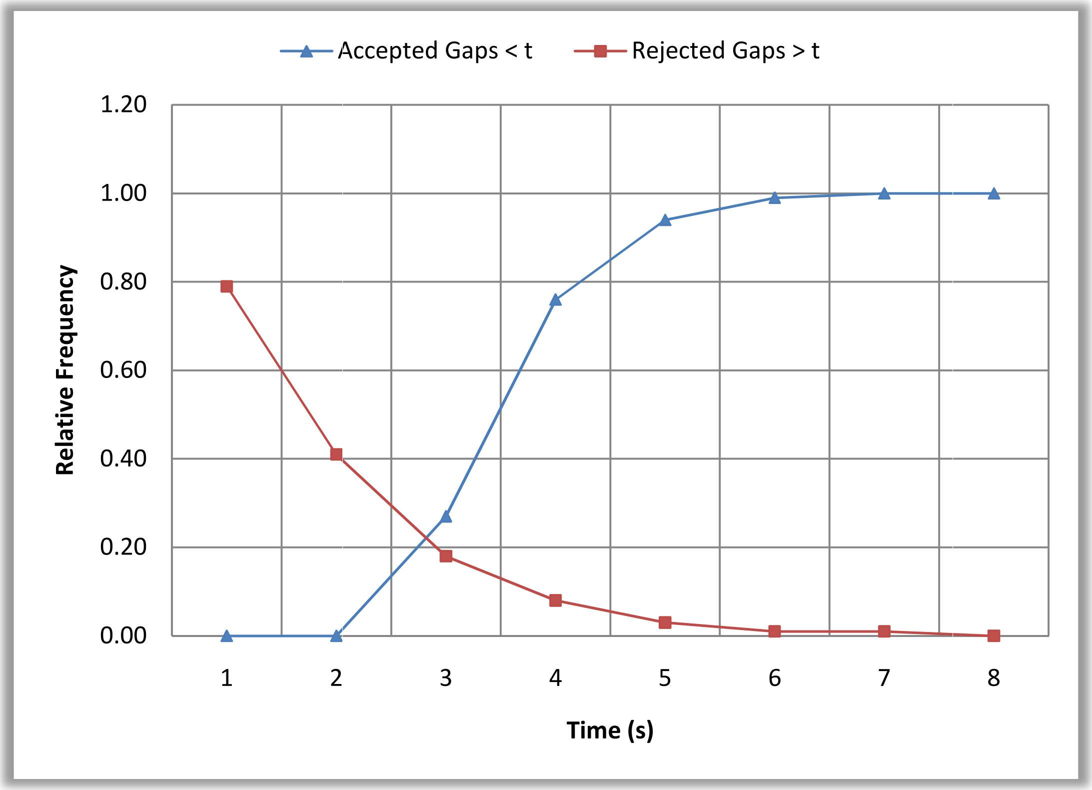

Figure 4 Critical gap at West Park Drive and East Park Drive, Wilmington, DE is 2.84s

4.1.2 Middletown, DE (Bunker Hill Road and Choptank Road)

The traffic volume at this location during morning and evening peak periods was very light. There were days when attempts to collect any useful data was futile since vehicles were arriving with virtually no other vehicles in the circulating lane. The researchers visited the site at different times during the morning, afternoon and evening in order to capture useful data for analysis. Table 4 is a summary of the accepted and rejected gaps obtained at this site. Figure 5 shows the critical gap obtained for this location.

Table 4 Data on gaps accepted or rejected by drivers at Bunker Hill Road and Choptank Road, New Castle County

Time gap (s)	Period observed: AM & PM	
	Accepted number	Rejected number
1	6	18
2	48	53
3	75	33
4	39	4
5	15	4
6	4	2
7	1	0
8	0	1

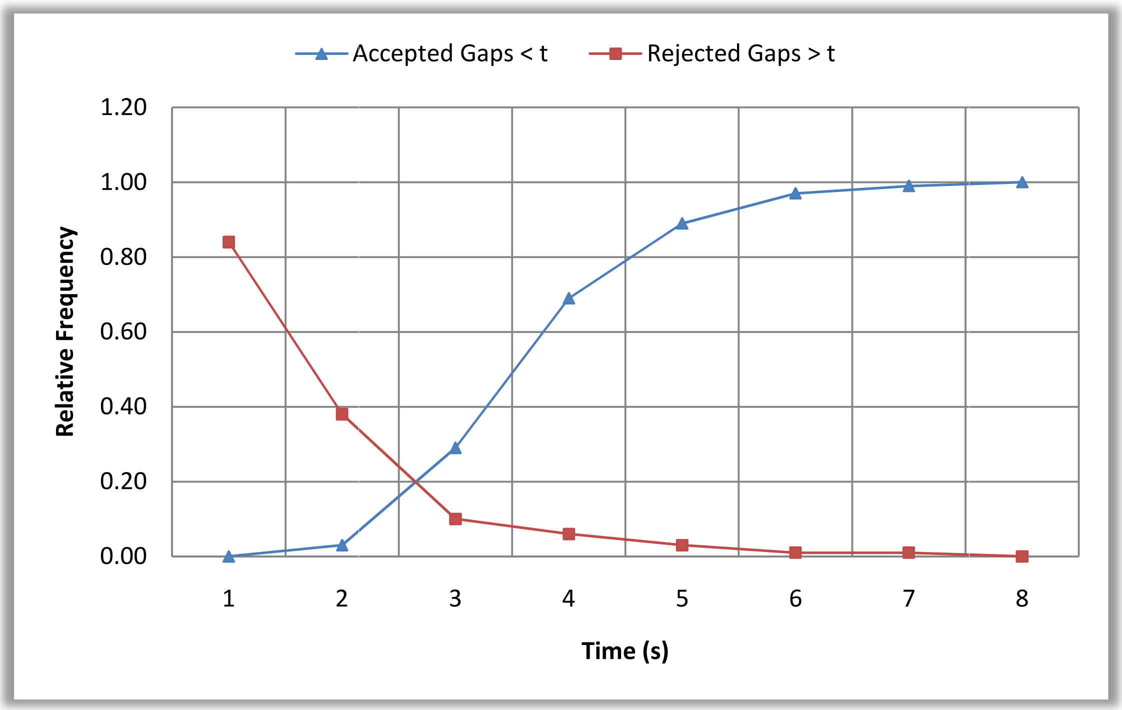

Figure 5 Critical gap at Bunker Hill Road and Choptank Road, Middle Town, DE is 2.68s

4.1.3 Rehoboth, DE (Rehoboth Avenue and Grove Street)

Table 5 is a summary of the accepted and rejected gaps observed at Rehoboth. Figure 6 shows the critical headway obtained for this location. This location records the smallest critical headway of the three locations studied in Delaware. It is also the roundabout that has been in operation longer than the rest. Table 6 presents the critical headway obtained at all three locations in Delaware.

Table 5 Data on gaps accepted or rejected by drivers at Rehoboth Avenue and Grove Street, Sussex County

Time gap (s)	Period observed: AM & PM	
	Accepted number	Rejected number
1	44	278
2	132	574
3	159	187
4	58	49
5	24	17
6	3	3
7	1	1
8	0	3
9	0	1

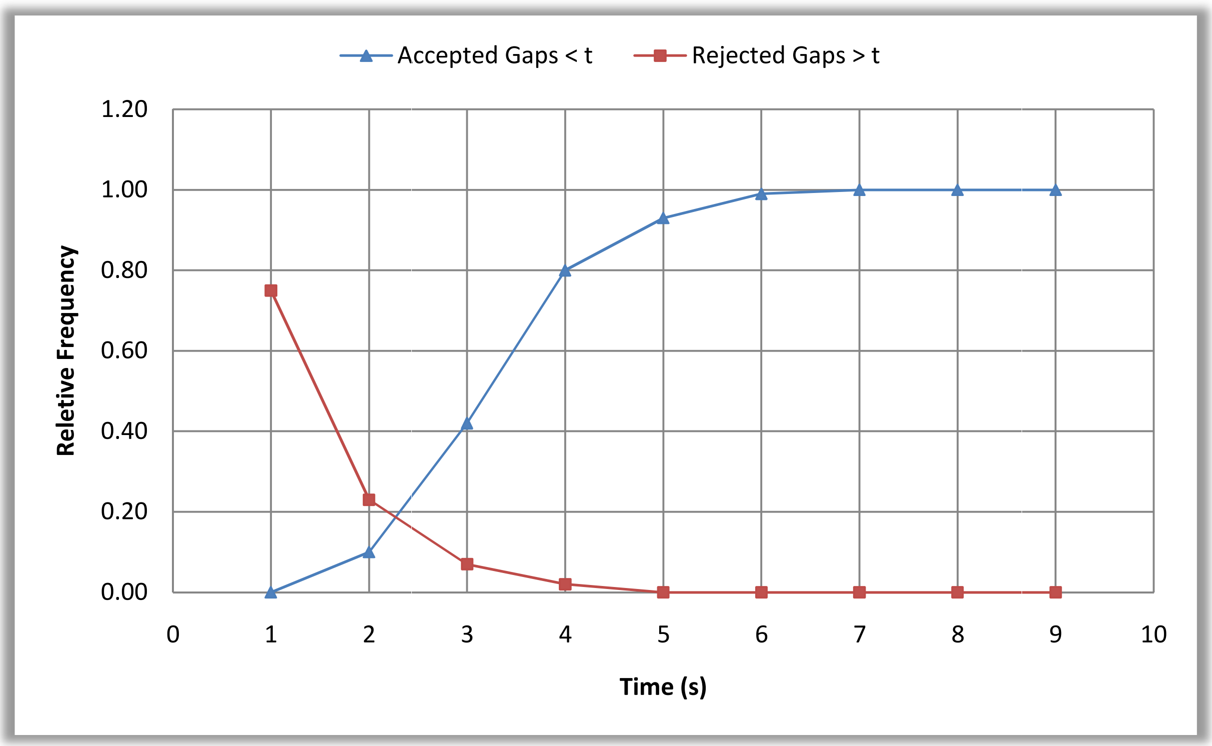

Figure 6 Critical gap at Rehoboth Avenue and Grove Street, Rehoboth, DE is 2.29s

Table 6 Critical headway for various locations in Delaware

Location	Critical Gap (s)
Wilmington, DE	2.84
Middletown, DE	2.68
Rehoboth, DE	2.29

4.2 Critical Gap – Maryland Observations

Two roundabouts were studied in Cecil County and Queen Anne's County in Maryland in summer of 2005. During data collection for this research work, part of the scope of works was to make an assessment of critical gap and follow up headway in Maryland to see how those parameters compare to Delaware's. Maryland is one of the leading States implementing modern roundabouts on the highway system. In order to assess the performance of the roundabouts after about 4 years of operation, a study [10] similar to what was carried out in summer of 2005 was done to collect data to determine the critical gap and follow up headway. Sections 4.2.1 and 4.2.2 show the results this study.

4.2.1 Chester, Maryland (Castle Marina Road and MD 18)

Table 7 shows the rejected and accepted gaps observed at the roundabout in Chester, Maryland. Figure 7 shows the critical headway obtained from the data.

Table 7 Data on gaps accepted or rejected by drivers at Queen Anne's County, MD 18@Castle Marina Road

Time gap (s)	Period observed: AM & PM	
	Accepted number	Rejected number
1	0	45
2	46	187
3	72	53
4	29	15
5	7	3
6	2	0
7	0	1

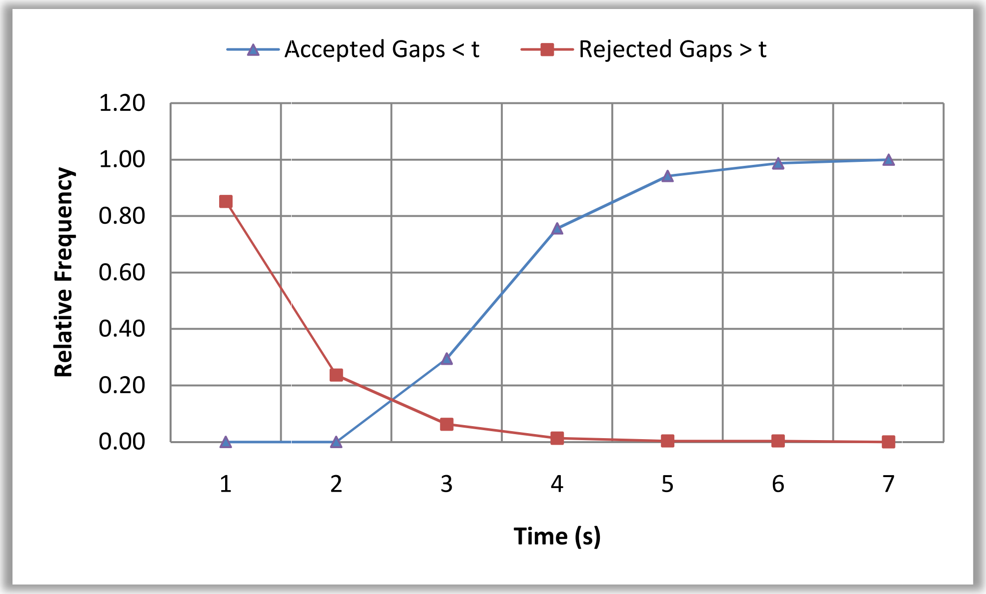

Figure 7 Critical gap at MD 18 and Castle Marina Road in Queen Anne's County had reduced from 3.91s when measured in May 2005 to 2.5s (June 2009)

4.2.2 Rising Sun, Maryland (MD 273 and MD 276)

Table 8 shows a summary of the accepted and rejected gaps at the roundabout in Rising Sun, Maryland. Figure 8 gives the critical headway obtained from this data. Table 9 compares the critical headways obtained when a similar research was carried out in the summer of 2005 to what was obtained in this research. It is obvious that at both locations the critical headway reduced over time.

Table 8 Data on gaps accepted or rejected by drivers at MD 273 at MD276, Cecil County

Time gap (s)	Period observed: AM & PM	
	Accepted number	Rejected number
1	23	0
2	68	53
3	41	59
4	12	20
5	2	4
6	1	1

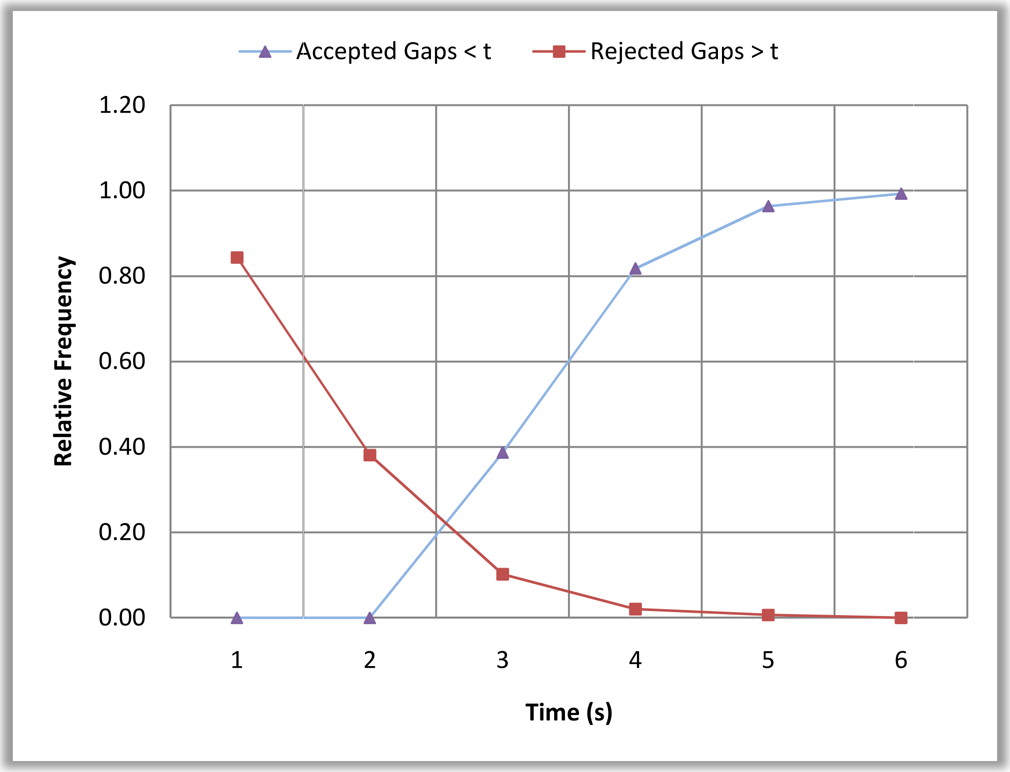

Figure 8 Critical gap at MD 273 and MD 276, Cecil County Maryland, reduced from 3.85s when measured in May 2005 to 2.60s (June 2009)

Table 9 Change in critical gap at Cecil County and Queen Anne's County in Maryland

Location	Critical Gap (seconds)	
	Vlahos (2005)	Current (2009)
Rising Sun, MD	3.85	2.60
Chester, MD	3.91	2.50

The results summarized in Table 9 show that at both locations the critical gap reduced. The critical gap had reduced from 3.91s to 2.5s for the roundabout at MD 18 and Castle Marina Road, and from 3.85s to 2.6s at MD 273 and MD 276. Even though a statistically rigorous approach was not used to establish this reduction in critical gap is indeed significant, the researchers surmise that it is a good indicator of a trend which has also been observed in other studies. NCHRP Report 572 [12] shows that the critical gap varies between 4.2s and 5.9s. This range of values is larger compared to the values obtained at the locations in Maryland in 2009. This considerable reduction in the critical gap over the four year period may be attributed to driver familiarity after the roundabout has been in operation for a while. If this is true, the change is noteworthy since the capacity of the roundabout is enhanced if drivers use a lower critical gap as shown in Equation 1. Therefore the capacity of the roundabout can be expected to improve over time as drivers get familiar, and planners can be less conservative in the design saving money upfront. Also this will lead to improvement in the LOS as well as delay and queue lengths since all these other parameters depend on the critical gap.

$$C_a = \frac{V_c e^{-V_c t_c/3600}}{1-e^{-V_c t_f/3600}} \quad (1)$$

Where

C_a = approach capacity (veh/h)

V_c = conflicting circulating traffic (veh/h)

t_c = critical gap (s), and

t_f = follow-up time (s)

For planners and designers the decrease in critical gap is significant because it means the roundabouts can perform better carrying more traffic with less adverse effects than originally anticipated under a higher value of the critical gap.

4.2.3 Comparison of Critical Gap, Delaware vs. Maryland

The critical gap evaluated for each location is shown in Table 10. Generally the sites in Maryland have lower values for critical gaps compared to sites in Delaware except Rehoboth. The two roundabouts with higher values (Wilmington and Middletown) are relatively new. The modern roundabouts at Wilmington and Middletown were opened to traffic in 2008 and Wilmington's was opened in 2003. Future studies carried out at these locations may help ascertain these preliminary observations, and if any changes in the critical gap will be consistent with the hypothesis in Section 4.2.2

Table 10 Comparison of critical gap for Delaware and Maryland (2009)

Location	Critical Gap (s)
Wilmington, DE	2.84
Middletown, DE	2.68
Rehoboth, DE	2.29
Rising Sun, MD	2.60
Chester, MD	2.50

4.3 Follow-Up Time

The follow-up time is the headway between two consecutive vehicles on the entry approach using the same headway in the circulating traffic to merge into the roundabout. Several merging maneuvers into the circulating traffic were observed along with follow-up time where it occurred and the results are summarized in Table 11. In the FHWA research [12] the smallest observed follow-up headway was 2.6s and the largest follow-up headway was 4.3s. Table 12 shows how the critical value and follow up time for each location compares to the NCHRP and HCM parameters.

Table 11 Mean follow up time at study locations

Location	Sample Size	Mean Follow Up Time (s)	Standard Deviation (s)
Wilmington, DE	201	2.09	0.72
Middletown, DE	67	2.37	0.83
Rehoboth, DE	540	1.98	0.64
Rising Sun, MD	61	2.23	0.62
Chester, MD	49	2.16	0.59

Table 12 Summary of observed critical gap and follow up headway

Location	Critical Gap (s)	Mean Follow Up Time (s)	NCHRP		HCM	
			Critical Gap (s)	Follow Up Time (s)	Critical Gap (s)	Follow up time (s)
Wilmington, DE	2.84	2.09	4.2 - 5.9	2.6 – 4.3	4.1 (upper bound) 4.6 (lower bound)	2.6 (upper bound) 3.1 (lower bound)
Middletown, DE	2.68	2.37				
Rehoboth, DE	2.29	1.98				
Rising Sun, MD	2.60	2.23				
Chester, MD	2.50	2.16				

4.4 LOS, Capacity, Delay and Queue Lengths

4.4.1 Level of Service (LOS)

The measure of effectiveness for intersections is the control delay and this is used to determine the level of service (LOS) at the intersection. Level of service according to the Highway Capacity Manual [14] is a "qualitative measure describing operational conditions within a traffic stream, based on service measures such as speed and travel time, freedom to maneuver, traffic interruptions, comfort and convenience." LOS is measured using letter grades "A" through "F"as shown in Table 13. Intersections with LOS A-D are considered to be performing at an acceptable level whereas LOS E-F are unacceptable.

There are variations in the thresholds for the LOS of signalized intersections and stop-controlled intersections because these two types of controls work differently and therefore generate different perceptions for drivers. This makes it difficult to draw comparisons in the level of service between these two types of controls. On the other hand there are some similarities in the dynamics when one compares a stop controlled intersection to a roundabout and therefore the thresholds used for determining LOS at a roundabout are identical to a stop controlled intersection. Data obtained from roundabout delay studies [12] generally support using the thresholds in HCM 2000 [14].

Table 13 LOS Criteria for signalized and unsignalized intersections

Level of Service LOS	Signals	TWSC and AWSC Control Delay (s/veh)	Roundabouts (s/veh)
A	≤10	0-10	0-10
B	>10-20	>10-15	>10-15
C	>20-35	>15-25	>15-25
D	>35-55	>25-35	>25-35
E	>55-80	>35-50	>35-50
F	>80	>50	>50

4.4.2 Capacity Analysis - NCHRP Approach

The approach in [12] is used to determine the capacity of a roundabout using local factors, critical gap and follow-up time that have been obtained from field studies. The model for single lane capacity is given below [14]:

$$q_{e,max} = \frac{q_c \exp\left(-\frac{q_c t_c}{3600}\right)}{1 - \exp\left(-\frac{q_c t_f}{3600}\right)}$$

Where

$q_{e,max} = entry\ capacity\ \ (veh/h)$

$q_c = conflicting\ circulating\ traffic\ \ (veh/h)$

$t_c = critical\ headway\ (s)$

$t_f = follow - up\ headway\ (s)$

The above equation can be simplified to the form

$$q_{e,max} = A.\exp(-B.q_c)$$

Where

$A = 3600/t_f$

$B = (t_c - t_f/2)/3600$

$t_c = critical\ headway\ (s)$

$t_f = follow\ up\ headway\ (s)$

The critical headway and follow-up headway obtained from a particular location can therefore be used to calibrate the model to determine the approach capacity of a roundabout. This procedure is used to develop the charts shown in Figures 9,10 and 11. A similar method is used to determine the NCHRP outputs in Tables 16, 17, 18, and 19.

Capacity, delay, queue length and the LOS estimates were made through computer simulation using the peak hour volumes obtained from DelDOT Peninsula Model and the operational parameters obtained from site observations. The peninsula model produced peak hour turning movements for the roundabouts at Wilmington, Middletown and Rehoboth. The capacity analyses performed were:

- Highway Capacity Manual (HCM) Lower Bound Analysis
- Highway Capacity Manual (HCM) Upper Bound Analysis
- Highway Capacity Manual (HCM) with Delaware-specific gap parameters
- Highway Capacity Manual (HCM) with Maryland-Specific gap parameters

- Sidra with recommended US environmental factor adjustment (1.2)
- Sidra without US environmental factor adjustment
- NCHRP 572 approach

No analysis for Middletown has been done since the configuration from the model (a three-legged intersection) does not match what is currently existing (four-legged intersection). Tables 14, 15, 16, 17, 18, 19 and 20 give a summary of the output from simulation to determine the capacity, LOS and delay.

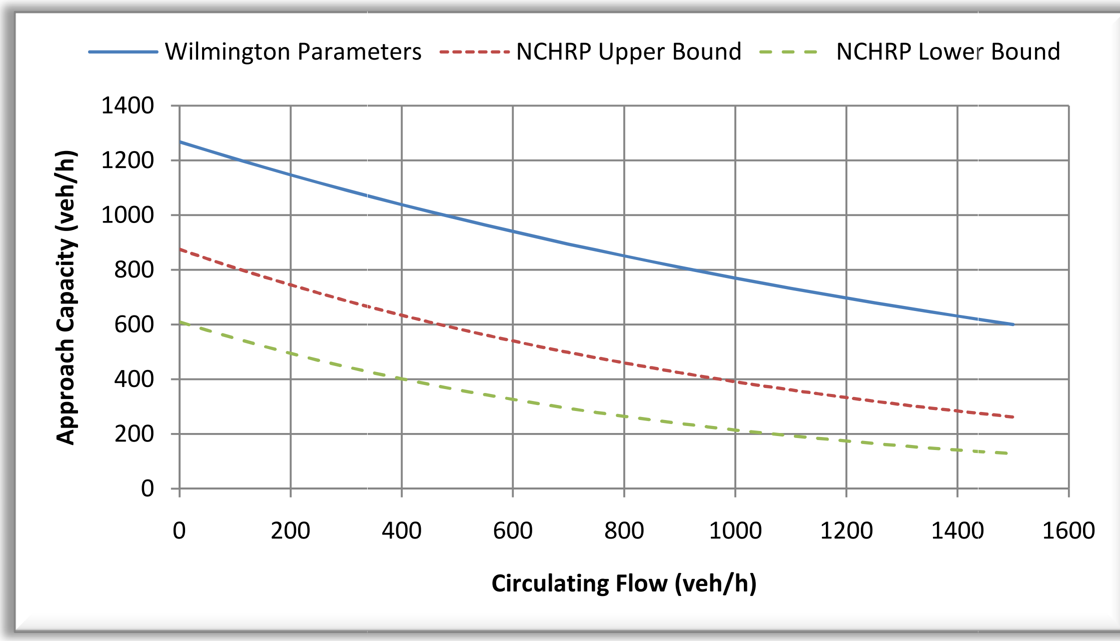

Figure 9 Approach capacity using the NCHRP methodology and parameters from Wilmington, DE

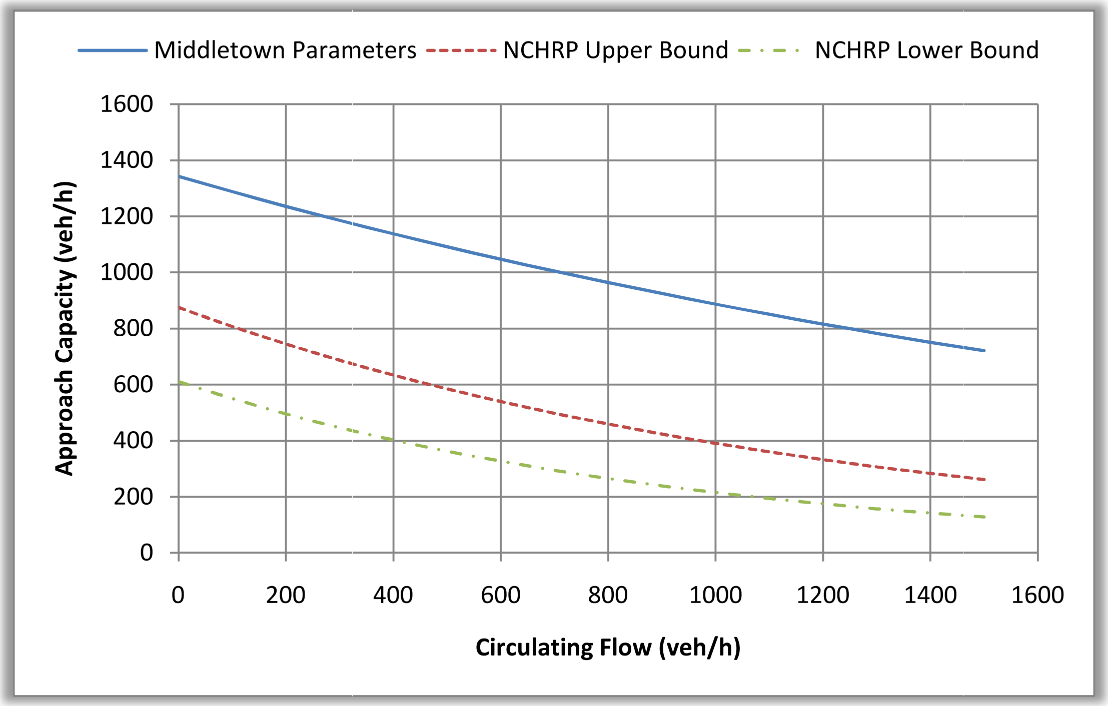

Figure 10 Approach capacity using the NCHRP methodology and parameters from Middletown, DE

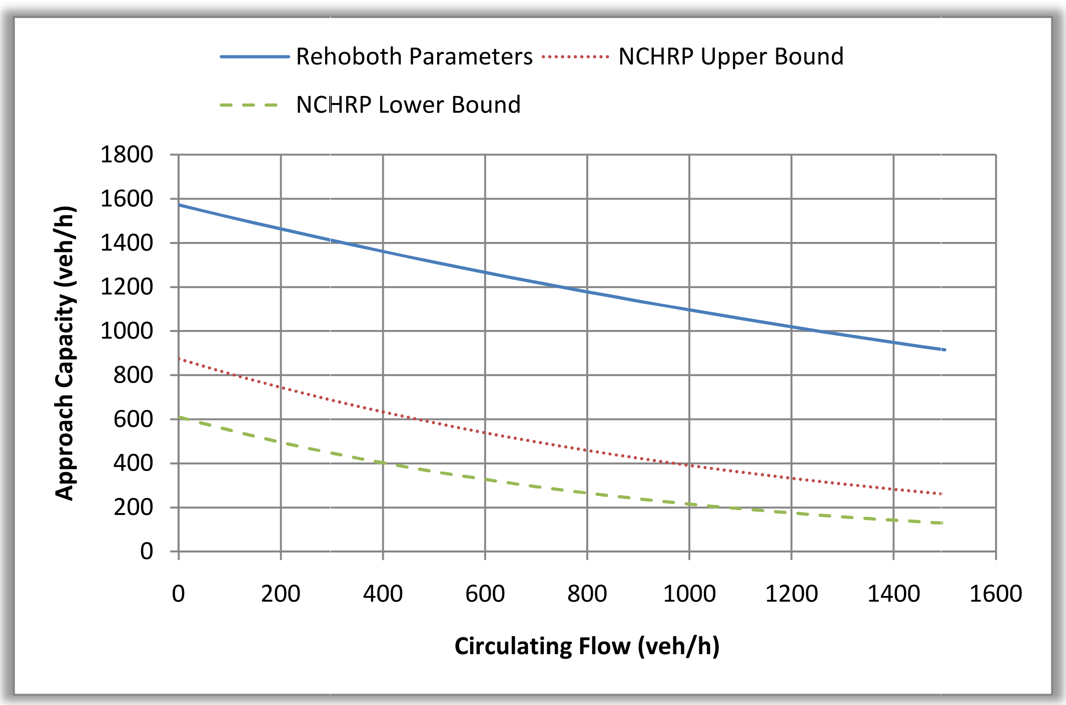

Figure 11 Approach capacity using the NCHRP methodology and parameters from Rehoboth, DE

Table 14 AM Capacity (v/c) analysis using HCM method

Table 14 Location	HCM (AM Analysis)															
	East				West				North				South			
	Upper bound	Lower bound	DE	MD	Upper bound	Lower bound	DE	MD	Upper bound	Lower bound	DE	MD	Upper bound	Lower bound	DE	MD
Wilmington	1094 (0.67)	898 (0.82)	1481 (0.50)	1478 (0.5)	968 (0.67)	785 (0.83)	1369 (0.48)	1389 (0.47)	-	-	-	-	1083 (0.46)	888 (0.56)	1472 (0.34)	1471 (0.34)
Middletown																
Rehoboth	969 (1.35)	786 (1.66)	1539 (0.85)	1493 (0.94)	946 (1.89)	766 (2.33)	1523 (1.17)	1373 (1.30)	483 (0.76)	364 (1.01)	1110 (0.33)	971 (0.38)	306 (2.22)	219 (3.11)	894 (0.76)	765 (0.89)

Table 15 PM Capacity (v/c) analysis using HCM method

Location	HCM (PM Analysis)															
	East				West				North				South			
	Upper bound	Lower bound	DE	MD	Upper bound	Lower bound	DE	MD	Upper bound	Lower bound	DE	MD	Upper bound	Lower bound	DE	MD
Wilmington	933 (0.62)	754 (0.76)	1481 (0.46)	1478 (0.46)	1013 (0.78)	825 (0.96)	1410 (0.56)	1421 (0.56)	-	-	-	-	1108 (0.45)	910 (0.55)	1493 (0.33)	1488 (0.34)
Middletown																
Rehoboth	884 (2.25)	711 (2.79)	1475 (1.35)	1326 (1.50)	845 (2.35)	676 (2.94)	1444 (1.38)	1295 (1.54)	284 (1.19)	202 (1.68)	864 (0.39)	736 (0.46)	284 (2.00)	202 (2.81)	864 (0.66)	736 (0.77)

Table 16 AM Capacity analysis (v/c) using NCHRP approach with site specific parameters

Location	Site Parameters											
	East			West			North			South		
	Capacity (veh/h)	Delay (s)	95 th Queue (ft)	Capacity (veh/h)	Delay (s)	95 th Queue (ft)	Capacity (veh/h)	Delay (s)	95 th Queue (ft)	Capacity (veh/h)	Delay (s)	95 th Queue (ft)
Wilmington	1447 (0.52)	5.2	79	1366 (0.49)	5.1	69	-	-	-	1469 (0.39)	4.0	48
Middletown												
Rehoboth	1538 (0.87)	14.9	324	1522 (1.20)	104.7	1283	1124 (0.34)	4.8	37	921 (0.76)	14.9	184

Table 17 AM Capacity (v/c) analysis using NCHRP approach with NCHRP default parameters

Location	NCHRP Default Parameters Upperbound											
	East			West			North			South		
	Capacity (veh/h)	Delay (s)	95 th Queue (ft)	Capacity (veh/h)	Delay (s)	95 th Queue (ft)	Capacity (veh/h)	Delay (s)	95 th Queue (ft)	Capacity (veh/h)	Delay (s)	95 th Queue (ft)
Wilmington	1289 (0.59)	6.7	101	1249 (0.53)	6.1	82	-	-	-	1290 (0.45)	5	60
Middletown												
Rehoboth	1249 (1.07)	58.2	705	1241 (1.47)	223.7	2038	1029 (0.37)	5.5	42	911 (0.76)	15.5	189

Table 18 PM Capacity (v/c) analysis using NCHRP approach with site specific parameters

Location	Site Parameters											
	East			West			North			South		
	Capacity (veh/h)	Delay (s)	95 th Queue (ft)	Capacity (veh/h)	Delay (s)	95 th Queue (ft)	Capacity (veh/h)	Delay (s)	95 th Queue (ft)	Capacity (veh/h)	Delay (s)	95 th Queue (ft)
Wilmington	1447 (0.48)	4.8	68	1406 (0.58)	6.0	97	-	-	-	1490 (0.39)	3.9	47
Middletown												
Rehoboth	1475 (1.38)	180	1972	1444 (1.41)	193.1	2059	892 (0.39)	6.6	47	892 (0.65)	11.2	124

Table 19 PM Capacity (v/c) analysis using NCHRP default parameters

Location	NCHRP Default Parameters											
	East			West			North			South		
	Capacity (veh/h)	Delay (s)	95 th Queue (ft)	Capacity (veh/h)	Delay (s)	95 th Queue (ft)	Capacity (veh/h)	Delay (s)	95 th Queue (ft)	Capacity (veh/h)	Delay (s)	95 th Queue (ft)
Wilmington	1282 (0.54)	6.1	85	1265 (0.64)	7.8	4.9	-	-	-	1298 (0.45)	5	59
Middletown												
Rehoboth	1217 (1.67)	310.4	2713	1201 (1.69)	320.4	2760	894 (0.39)	6.6	47	894 (0.65)	11.1	123

Table 20 Capacity (v/c) analysis using SIDRA

Location	SIDRA (AM)				SIDRA* (AM)				SIDRA (PM)				SIDRA* (PM)			
	Capacity (veh/h)	95th Queue (ft)	Delay (s)	LOS	Capacity (veh/h)	95th Queue (ft)	Delay (s)	LOS	Capacity (veh/h)	95th Queue (ft)	Delay (s)	LOS	Capacity (veh/h)	95th Queue (ft)	Delay (s)	LOS
Wilmington	3609 (0.54)	123	4.6	A	3609 (0.54)	123	7.5	A	3323 (0.62)	159	7.4	A	3323 (0.62)	159	7.4	A
Middletown																
Rehoboth	3147 (1.32)	1609	30.2	C	3147 (1.32)	1609	30.2	C	3387 (1.44)	1680	33.6	C	3387 (1.44)	1680	33.6	C

*without environmental factor

4.4.3 Delay

The average delay experienced at each intersection was extracted from the video. The values represent the stopped delay. Delay is minimal and it is consistent with the uncongested observations at the site. The computed delays and the associated LOS are shown in Table 21.

Table 21 Delay per vehicle estimated at each roundabout

Location	Total Delay (s)	Number of Observations	Average Delay per vehicle (s)	LOS
Middletown, DE	279	115	2.42	A
Wilmington, DE	200	80	2.50	A
Rehoboth, DE	2326	1113	2.09	A
Chester, MD	660	304	2.17	A
Rising Sun, MD	346	147	2.35	A

4.4.4 Queue Lengths

Tables 16, 17, 18, 19 and 20 give the 95th percentile queue lengths of either an approach or the intersection as a whole. Queue lengths grow with heavy delay. In an urbanized network where there might be an adjacent intersection, queue lengths are important in order not to disrupt flow at nearby intersections.

4.5 Geometric Features

Geometric features of the roundabout such as the diameter of the inscribed circle, number of circulatory lanes and number of entry lanes have an impact on capacity. For instance, under low circulatory flow conditions, a roundabout with two entry lanes will have nearly twice the entry capacity as one lane [15]. Apart from that, the calming effect on traffic and the ease of maneuvering by trucks is related to the physical dimensions of the components of the modern roundabout.

One problem that confronted DelDOT was the inability of oversized farm vehicles to negotiate the roundabout located at the intersection of Choptank Road and Bunker Hill Road in Middletown, New Castle County. This raised questions about the adequacy of the size of the roundabouts and the ability of oversized farm vehicles especially to use these roundabouts without any problems. One of the tasks of this project was to make field observations of heavy vehicle use of the roundabouts to assess the adequacy of the design.

The sites in Delaware had few heavy vehicles (buses and trucks) coming through the roundabout during the field observations. A few buses and trucks (no single trailer or multi-trailer trucks were observed) observed on the site entered and exited the roundabouts successfully without any issues with the turning and tracking of the rear axles. There were not observations of any "oversized farm vehicles. Also, there were no observations of tractor trailers (FHWA Class 7-12) using the roundabout and no definitive statements can be made on the adequacy of the size or the roundabout to accommodate these types of vehicles. DelDOT has addressed this problem by using a design standard with the following provisions: no vertical curb; reinforced grass shoulders; larger aprons; and less sloping aprons.

However, field observations carried out at the roundabout at MD 273 and MD 276 in Cecil County had some tractor-trailers (FHWA Class 8) which used the roundabout without any problems. The roundabout at this location has an inscribed diameter of 141ft, island diameter of 113ft, a circulatory lane width of 14ft and a truck apron of width of 4ft.

The geometric dimensions of the roundabout affect the ease of movement of vehicles especially heavy vehicles, and also impact the speed of vehicles around the central island and therefore affect the gap acceptance process and the capacity [6]. No such study was conducted in the report since the limited number of roundabouts constructed in the state will not provide adequate data to establish any meaningful correlations.

4.6 Field Observation

4.6.1 Driver Behavior

Driver behavior approaching the roundabout and merging has significant impact on the performance of the roundabout. The gaps that drivers reject or accept in order to merge into the circulating lane determine the impact on delay as well as capacity. If drivers require longer gaps to merge, they tend to wait longer and that causes further delay for them and all other vehicles queued behind.

The observations on the site revealed that generally most drivers seemed comfortable and did not show any sign of trepidation merging into available gaps or lags on arrival at the yield line. However a few drivers were stopping when there was no conflicting vehicle even though the sign at the entry is a YIELD. Other drivers already in the circulating lane would yield to vehicles at the approach leg causing some unsafe situations for drivers behind who were not expecting vehicles ahead to stop. Also drivers waiting to merge into the roundabout waited longer than necessary because vehicles exiting the circulating lane were not using the turn signals. The excessive wait time and the inappropriate yielding have an adverse effect on the capacity of the roundabout. This goes to underscore the fact that some drivers are still not very familiar with how a modern roundabout operates. There were no observations of entering vehicles making forced entries causing circulating vehicles to take evasive action. Forced entry will usually result from long delays at the entry leg. Also throughout the observation period, no vehicle passed the wrong side of the central island and smaller vehicles were not driving over the truck aprons.

Table 22 below summarizes the instances where drivers acted contrary to expectation which in this text is classified as "bad behavior."

Table 22 Observations of drivers that act contrary to expectation when merging into a roundabout

Roundabout	Time	Approach Volume	Circulation Volume	"Bad Behavior"
Wilmington	4:00-5:15	945	152	18
Middletown	6:15-8:30	216	159	4
	3:30-6:00	260	220	11
Rehoboth	6:30-9:00	1147	582	1
	12:15-2:00	2024	609	14
Rising Sun	7:00-8:15	372	264	1
Chester	7:15-8:30	252	718	10

Another driver observation carried out was to determine their interaction with pedestrians waiting to cross the streets. Two types of yield can be described [16]: active yield and passive yield. In "active yield" motorists slowed or stopped for a pedestrian crossing the street or waiting to cross, and the pedestrian was the only reason the driver stopped or slowed down. In "passive yield" the driver allows pedestrians to cross only because they were already stopped for another reason, either because of a queue or a prior pedestrian crossing event. One of the methods for assessing safety is to measure conflicts. A conflict occurs when a driver or pedestrian takes evasive action or changes course to avert a collision. No conflicts were observed however the number of crossing events for pedestrians was extremely few and no conclusive statements can be made at this time.

4.6.2 Pedestrian Behavior

Pedestrian activity was rather limited at all three locations. There was virtually no pedestrian found at the roundabout in Middletown (Bunker Hill Road and Choptank Road) during the period of data collection. At East Park Drive and West Park Drive, extremely few pedestrians were observed, usually joggers, during data collection. Rehoboth Avenue and Grove Street had more pedestrian activity but less than one would have imagined for the summer beach season. It appears the distance (about a mile from the shore) was a bit far off and therefore driving or biking was the preferred option. Pedestrians were mostly adults and in a few instances adults with youths. There were no observations of pedestrians with disabilities including blind pedestrians.

One of the goals for pedestrian observations was to see how pedestrians navigated their way around the intersection making use of crosswalks or otherwise and how drivers in turn reacted to pedestrians. The few pedestrians observed at Rehoboth generally crossed the streets at the crosswalks making use of the islands as refuge when necessary. Another observation of interest was where crossings were being initiated – within boundaries of the crosswalks or otherwise. Most pedestrians crossed the street at the crosswalks provided however a few did not use this designated location for crossing. Some pedestrians crossed at the yield line, the entry point into the circulating lane, instead of the crosswalk. This caused further delay to vehicles which could otherwise have merged into the circulating lane had the pedestrians used the crosswalk behind these vehicles. Also in one instance a man was observed walking a dog on the truck apron – a location where pedestrians are not permitted to be. This has been captured in Figure 8 below. All the pedestrian crossings observed were either "normal" or pedestrian "hesitates" before crossing. These terminologies are define as follows [12]: "normal" implies pedestrians cross the street at normal pace or walking speed; "hesitates" implies pedestrian hesitates on the curb or splitter island because of an approaching vehicle while trying to make visual contact with driver.

Figure 12 A pedestrian in restricted area of roundabout

Pedestrian access to highway facilities is a very important subject matter and this has been the subject of much debate. Even more important is accessibility to pedestrians with vision impairment which is one of the challenging issues across the nation when it comes to installation of roundabouts. In some instances there have been litigations to challenge the construction or roundabouts because it makes it more difficult for pedestrians generally but especially those with disabilities to cross compared to signalized intersections. Pedestrians with vision impairment are required to (1) locate the crosswalk, (2) correctly orient the direction of the crosswalk, (3) determine when it is safe or permissible to cross, and (4) have sufficient time to cross. Roundabouts unlike other forms of intersection control have a continuous flow of traffic with no fixed stop intervals pedestrians can use to cross the intersection. Rouphail et. al [17] therefore argued that visually impaired pedestrians cannot depend on the auditory cues they use to cross signalized intersections because roundabouts essentially operate on a continuous flow basis. Moreover exit flow vehicles as well as circulating vehicles tend to mask the cues making it difficult for blind pedestrians to judge available gaps for crossing. Furthermore many new cars have much quieter engines and therefore make it even difficult to rely on auditory queues. Schroeder et al [18] noted that this issue is further complicated at multilane roundabouts compared to single lane roundabouts. Crossing becomes more difficult as the volume of vehicles increases. In addition Long et. al. [19] mentioned a "multiple-threat" situation where visually impaired pedestrians can get trapped in the middle of two lanes and cannot complete a crossing. This situation arises when crossing multiple approach lanes, a visually impaired pedestrian is not able to determine that vehicles have yielded in both lanes or that there is an adequate gap to allow crossing of both lanes. In other words, crossing is initiated when there is adequate gap only in the near lane or when a driver in the near lane yields but on arrival at the second lane there are no useable gaps or drivers do not yield. In view of these issues facing the visually impaired pedestrians, the United States Access Board recommends [20] that at "roundabouts with multi-lane crossings, a pedestrian activated signal complying with R306 shall be provided for each segment of each crosswalk, including the splitter island. Signals shall clearly identify which crosswalk segment the signal serves."

The three roundabouts studied in this research did not have pedestrian signalization options which may aid pedestrians to cross the streets especially the visually impaired pedestrians. The volume of pedestrians and traffic were not so high to create any notable additional hazards for pedestrians crossing the streets. No observations of blind pedestrians or posted signs for blind pedestrians were seen at the sites. It appears pedestrian signalization may be an option that will enhance safety for both all pedestrians especially the visually impaired.

4.6.3 Bicyclist Behavior

During the period of data collection, no bicyclist was found at any of the roundabouts except Rehoboth Avenue and Grove Street. The bicyclists were generally beach goers. No bike paths are provided in the circulating lanes. Observations Rehoboth showed that that most bicyclists used the travel lanes to maneuver around the roundabout as shown in Figure 13 below. In some instances some bicyclists kept to the edge of the road thus sharing the lane with drivers. Others however drove close to the middle of the lane so other drivers could not pass. Some bicyclist using the travel lanes will sometimes use hand signals to indicate the direction they are traveling at the roundabout. Very few bicyclists used the sidewalks as they approached the roundabout and only did so when pedestrians were not present. No definitive statements can be made about bicycle-pedestrian interactions at this time since there were hardly any such events.

Figure 13 Bicyclists use lanes to navigate roundabout

4.7 Safety Analysis

The safety of modern roundabouts is well documented and brief highlights are provided in Section 2.2.2. The main features of a modern roundabout that makes it perform better with respect to safety are reduction in the number of conflict points and lowering of the speed of circulating and approaching vehicles [21]. The aspect of speed reduction was attested to by a police officer on duty monitoring traffic near the roundabout. In a brief interview the police officer revealed that the roundabout has had tremendous impact on movement of traffic in the area and excessive speeding in the area had also declined. Another objective was to assess the accidents occurring at each location. An acceptable basis for comparison should be based on the accident rate (rate per million entering vehicles, RMEV) which takes into account the number of vehicles that used the intersection – a measure of the exposure at the location. The crash rates of each location are computed and in instances where a modern roundabout replaced another form of control, a comparison of the crash prior to the construction of the modern roundabout is compared to the crash rate after the roundabout is operational. The crash rate per million entering vehicles (RMEV) will be used as the standard measure. Accident reports were solicited from the police in each jurisdiction. Since the Delaware Department of Transportation archives these reports, accident reports were obtained from the department. It must be noted however that no all accidents result in an incident report especially when the damage involved is minor. A true measure of the accident rate at each location will be from the logs of the police dispatcher. Unfortunately such information is not available at this time. Therefore the number of accidents used in each analysis is based on information from the accident reports obtained from the Department of Transportation.

4.7.1 Crash Analyses

In order to perform safety analysis of each roundabout intersection related crashes were studied. Intersection related crashes were assumed to be all accidents that occurred within 100ft of the intersection. Comments in the accident report were also used to get a sense if perhaps approaching a roundabout was a factor. The accident data covers January 2003 through

December 2009. Comparative analysis of accident rates before construction of the modern roundabout and rates post construction of the roundabout have been done. Out of the three roundabouts studied in the state of Delaware, the one located in Wilmington (East Park Drive and West Park Drive) is on a new alignment so no "before" accident analysis can be performed for this intersection. The roundabouts at Middletown (Bunker Hill at Choptank Road), and Rehoboth (Rehoboth Avenue at Grove Street) were converted to modern roundabouts and therefore a "before" and "after" study can be analyzed to assess the impacts of the modern roundabout on safety.

The modern roundabout at Wilmington was opened to traffic in August 2007, Middletown in April 2008, and Rehoboth in May 2004. Tables 23, 24 and 25 summarize the number and type of accident experienced at each location from January 2003 through December 2009. The crash rate, rate per million entering vehicles (RMEV), has been calculated as follows:

$$RMEV = \frac{crashes/year}{approach\ ADT * days/year} * 10^6$$

Table 23 Accident data at Wilmington, DE (opened to traffic in August 2007)

Severity	2007	2008	2009	Annual Average
Fatal				
Personal Injury				
Property Damage				
Total		0	0	0
AADT (entering)		NA	NA	NA
RMEV				

Table 24 "Before" and "After" Accident data at Middletown, DE (opened to traffic in April 2008)

Severity	Before							After		
	2003	2004	2005	2006	2007	2008	Annual Average	2008	2009	Annual Average
Fatal										
Personal Injury										
Property Damage			1		1		0.381	1		0.500
Total			1		1		0.381	1		0.500
AADT (entering)	1320	1334	1352	1311	1316	1477	1352	1477	1477*	1477
RMEV							0.772			0.927

*Used value from 2008

Table 25 "Before" and "After" Accident Data at Rehoboth, DE (opened to traffic in May 2004)

Severity	**Before**						**After**						
	2000	**2001**	**2002**	**2003**	**2004**	**Annual Average**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**Annual Average**
Fatal						0.000							0.000
Personal Injury				1		0.500		1					0.167
Property Damage		1	1	2		1.000	1	2	2	1			1.000
Total				3		1.500	1	3	2	1			1.167
AADT (entering)	NA	NA	NA	21833	15923	18878	15923	16114	14449	14732	14016	14828*	15010
RMEV						0.218							0.213

*Value was estimated using average of 4 previous years.

Middletown: The crash rate before construction of the roundabout (0.772) is lower than the crash rate after construction (0.927). This is not entirely unexpected since generally it is acknowledged that accidents tend to increase for non-injury producing accidents whereas injury producing accidents are dramatically reduced. Also the lack of complete data for analysis means no definitive statements can be made about this site at this time. While accident data is averaged over about 5years in the pre-roundabout case, data available for post-roundabout period spans only 2 years. A few more years of accident data collection will give a much more statistically reliable estimate of the trend in accidents at this location.

Rehoboth: The crash rate at Rehoboth prior to the construction of the roundabout is 0.218 (two year average) and post construction is 0.213 (six year average). These averages do no span equivalent time periods and therefore no reliable statements can be made here about the improvement in safety.

5 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Modern roundabouts are becoming increasingly popular alternatives, replacing STOP controlled intersections (two-way, three-way and all-way-stop controlled intersections) and in some cases even traffic signals. In instances where roundabouts have replaced other types of intersection control, the benefits in terms of safety have been remarkable and many examples can be found in the literature. Individuals who were initially adamantly opposed to roundabouts are now willingly embracing them as a result of good experiences and other benefits. However there are yet many more that still oppose the installation of roundabouts and granted modern roundabouts are not the solution to every intersection problem. A good way to win over these skeptics is situations where a well designed modern roundabout brings with it tangible results that those who oppose cannot refute.

Modern roundabouts are relatively new in Delaware and sufficient data is not available yet to do a comprehensive before-and-after study. This research obtained the critical gap and follow-up headway for the various locations studied. It also came to light that the critical gap had reduced for the sites in Maryland where similar studies were carried out five years ago. Although a statistically robust analysis is lacking it appears this change may be due to driver familiarity. Our field observations showed some drivers in the circulating lane yielding when they had right of way and did not have to. Other drivers came to a complete stop when there was no conflicting traffic. In due time as drivers learn better how to drive the modern roundabout, there is no doubt these behaviors which impact performance of the roundabout will be corrected. A statistically robust methodology must be used however to establish that this change is indeed significant and also quantifying this change which no doubt will impact the design process. If the critical headway indeed decreases as the observations suggest, then over time there will be an incremental improvement in the performance of the roundabout which means delay will reduce, emissions will reduce, queue lengths will reduce and capacity will improve. This in turn could also impact the design philosophy when making provisions for future growth in traffic, a less conservative design could provide some savings upfront.

Generally, it appears all the roundabouts are operating below capacity and the level of service is acceptable except Rehoboth where capacity appears to be exceeded. These observations are based on forecasted traffic volumes from the DelDOT Peninsula Model. Observations during data collection did not indicate any excessive queuing or delays that will be associated with capacity being exceeded. Rehoboth was the only location where pedestrian and bicyclist activities were significant as a result of the attraction of the beaches. No significant delays were imposed on motorist by bicyclists/pedestrians, and vice versa. No audible pedestrian signals were observed at any of the sites which could aid especially blind pedestrians to cross the streets.

Another object of this study was the impact of the modern roundabout on safety. Sufficient data was not available to make conclusive statements yet. It is a known fact however that roundabouts significantly improve safety by reducing injury producing accidents. Data used in this analysis was based solely on accidents for which accidents reports were generated by the police. This obviously precludes other incidents that were not recorded by the police.

5.2 Recommendations

Further monitoring of the performance of the modern roundabout in Delaware will yield more information to impact the planning and design of the roundabouts. Especially the parameters of interest will be the critical headway and the follow-up headway which are used in the capacity analysis. This research provided these parameters that can be used to design modern roundabouts in Delaware. Also, one of the primary concerns of any intersection is accessibility to blind pedestrians. While some modern roundabouts have accessible pedestrian signals to help the visually impaired to cross, it appears provision is not mandatory according to the MUTCD. DelDOT may consider monitoring the roundabouts periodically to assess pedestrian-vehicle interactions to see if there is a need for pedestrian crossing signals.

5.3 Future Research

Periodic monitoring of the new and existing roundabouts in the state should be implemented. It is a known fact that roundabouts a safer because they reduce severe crashes however minor crashes may increase probably because drivers are not very familiar with its mode of operation. The crash experience in Delaware should be monitored to determine what the causes are and how they can be mitigated. This study can also attempt to quantify instances where drivers create unsafe situations by flouting the rules of operation (bad behavior) to give a sense of how well drivers use the roundabouts in Delaware.

Further field experiments should be carried out to capture additional data on critical headway and follow-up headway. The observations in this report are based on limited information collected at each site. A statistically more accurate result will be realized from an extended study which yields more data.

There should be an assessment of pedestrian vehicle interactions to determine the optimal pedestrian volume without installation of accessible pedestrian signals for an effective roundabout operation. The studies should cover determination of average pedestrian delay at the intersection, and average pedestrian induced vehicle delay. This will enable DelDOT formulate a policy for the provision of pedestrian crossing signals at roundabouts in order to ensure effective throughput of both pedestrians and vehicles. This study should also include optimal location of the crosswalk and the type of crosswalk i.e. staggered or straight. A staggered crosswalk that allows pedestrians to face oncoming vehicles when crossing is believed to enhance safety. However another school of thought suggests that is creates problems for pedestrians with vision impairment as well as pedestrians in wheel chairs especially where the median is narrow. A study on the applicability at a specific location in Delaware can be done and the appropriate policy formulated.

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