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Operational Improvements at Traffic Circles: Safety Analysis

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16. Abstract

The purpose of this study was to improve the safety and operation at three traffic circles in New Jersey. To do this, data were collected at the traffic circles to allow researchers to model the circles using the PARAMICS software simulation package. Once operational and safety factors were evaluated at the circles, alternatives for improvement were developed. The PARAMICS model was then utilized to evaluate the costs and benefits of each alternative. To augment the simulation work, empirical analysis was also performed using two model forms.

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SAFETY ANALYSIS

The purpose of this project is to improve the safety and operation of three traffic circles in New Jersey. To do this, data were collected at the traffic circles to allow researchers to model the circles using the PARAMICS software simulation package. Once operational and safety factors were evaluated at the circles, alternatives for improvement were developed. The PARAMICS model was then utilized to evaluate the costs and benefits of each alternative. To augment the simulation work, empirical analysis was also performed using two model forms, one British and one Australian.

The safety analysis is divided into seven chapters: Techniques for Evaluating Safety; Review of Safety Models; Safety Treatments; Safety Methodology; and, one chapter for each traffic circle under study. For each traffic circle chapter, there is a description of the circle, an accident history discussion, a detailing of recommended improvements, figures and discussion about the 24-hour traffic volume counts, a discussion of the empirical analysis and results obtained, a description of the simulation-based analysis and results, and finally a summary.

Techniques for Evaluating Safety

<u>Introduction</u>

This section is intended to provide an overview of methods used to evaluate safety at traffic circles and roundabouts. In addition, it looks at models that predict measures of safety. These models can be used to develop alternatives for improving traffic circles. Finally, this section includes an exploration of which data need to be collected and how they may be obtained in order to be used in the predictive safety models.

In order to evaluate the safety at each of the traffic circles, data were collected that allowed engineers to model the circles using the PARAMICS software package. Once operational and safety factors were evaluated at the circles, alternatives for improvement were created. The PARAMICS model was then utilized to evaluate the costs and benefits of each alternative.

The data that were necessary for performing this type of analysis are specified below. From an operational standpoint, the following data were required:

- Velocity vectors at the following locations
  - Entering the circle
  - Circulating within the circle (measured at the splitter island)
  - Exiting the circle
- Traffic volumes
- Delays
- Queues entering, circulating, and exiting the circle
- Vehicle gaps
- Geometry of the circle

In addition to the data above, the collision history was also necessary to evaluate the safety of the facility. This was used to establish collision patterns at the circles and the potential causes of those collisions.

The intent of this project was to make both operational and safety improvements at the three traffic circles involved. This section begins with a brief overview of safety concerns and actions that should be taken to improve safety at traffic circles and roundabouts covered in *Accidents at 4-Arm Roundabouts* by Maycock and Hall, *Roundabout Design Guidlines* by Ourston & Doctors, the Austroads *Guide to Traffic Engineering Practice*, *Working Paper #2*: Safety Models from NCHRP Project 3-65 by Persaud and Lyon, and FHWA's *Roundabouts: An Informational Guide*.[See references 1,2,3,4, and 5] Next, this section covers safety models and the data required for their use. Finally, this chapter includes an outline of how this data may be collected and extracted for use in this project.

Review of Safety Features

One of the largest factors affecting safety at traffic circles and roundabouts is related to speed in the facility. While high speed is a major concern, another is the difference in speeds between entering and circulating traffic, and between circulating and exiting traffic. Because it is the difference in these speeds (measured as a vector) that affects safety, it is not only the magnitude of the speeds that matters, but the difference in the directions the vehicles are traveling. When there is either a very large or very small angle between the speed vector of entering traffic and the speed vector of circulating traffic, the potential for a collision exists.

The *Roundabout Design Guidlines* points out safety issues with two-wheeled vehicles and trucks, but does not make specific recommendations for how to improve safety related to these issues.(2) The document does suggest that roundabouts with the following features have the most problems: inadequate entry deflection, which causes high entry speeds; long straight sections of circulatory roadway leading to deceptively tight curves; and sharp turns into exits.

Austroads' *Guide to Traffic Engineering Practice* includes a section on roundabouts.(3) It contains only a very small section related specifically to safety, but discusses factors such as speed control and deflection, sight distances, superelevation and drainage, pedestrians and bicycles, line marking and striping, proper lighting, and how these affect safety and operations in roundabouts. Austroads attributes good safety at roundabouts to the following design features: low speeds for all movements; elimination of high angles of conflict (to reduce relative speeds between conflicting vehicles); simple decision making at the point of entry; and long splitter islands to provide advance warning of the facility. According to Austroads, the deflection of vehicle paths entering a roundabout is the most important factor affecting safety. This deflection can be achieved by adjusting the geometry of the entry or ensuring that vehicles going straight through the facility are deflected by one of the following methods: alignment of the entry and shape, size and position of the splitter islands; placement and size of central island; or use of a staggered or non-parallel alignment between any entry and exit.

The Federal Highway Administration's *Roundabouts: An Informational Guide* contains a large section on safety in roundabouts.(5) It attributes accidents at roundabouts to the number and magnitude of conflict points. It describes a conflict point as the location where the paths of two vehicles, pedestrians, bicycles, etc. merge, diverge, or cross one another. It suggests that the characteristics of the conflict point (exposure, severity, and vulnerability) affect the number of accidents that occur and their severity. Exposure refers to the product of the two conflicting stream volumes at the point of conflict. Severity refers to the relative velocities of conflicting streams. As was mentioned earlier, the relative velocity is a measure of angle and speed while vulnerability is a measure of the ability of a person or vehicle in a conflicting stream to survive a collision.

The FHWA's *Roundabouts: An Informational Guide* discusses three types of vehicle-vehicle conflicts: queuing conflicts, merge and diverge conflicts, and crossing conflicts.(5) Queuing conflicts occur when vehicles back up and one vehicle is rear-ended by a following vehicle. These accidents are less severe than the other types due to a small relative velocity between the involved vehicles. Queues occur when there are too few gaps for vehicles to accept. Therefore, the distribution of gaps should be measured to predict whether queuing conflicts would occur.

Merge and diverge conflicts occur when two streams of traffic are joining or separating, respectively. These conflicts often result in sideswipe or rear-end collisions. While merge and diverge conflicts result in less severe collisions than crossing conflicts, they can be more severe than queuing conflicts because the relative velocity between the vehicles is higher and because the sides of cars tend to be weaker than the front and back.

Crossing conflicts result from the intersection or crossing of two traffic streams. These collisions can be extremely severe because of the high relative velocities between the vehicles.

Furthermore, the FHWA's *Roundabouts: An Informational Guide* discusses pedestrian and bicycle conflicts with vehicles.[5] The conflicts take place where pedestrians cross entering and exiting traffic. The risk of a collision is increased if there are multiple lanes of exiting or entering traffic as opposed to a single lane. Bicycle-vehicle conflicts can exist in the same location as pedestrian-vehicle conflicts if cyclists are using bike lanes or sidewalks. However, some cyclists may choose to ride on the roadway and follow vehicle rules through the facility. If this is the case, then the types and points of conflict will be the same as for vehicle-vehicle conflicts.

In *Working Paper #2 for NCHRP Project 3-65*, Persaud and Lyon [4] discuss predictive safety models that were developed in the U.K., Australia, and Sweden. Based on these models, Persaud and Lyon[4] were able to determine relationships between collisions and geometric characteristics of roundabouts such as number of approaches, radius of central island, number of lanes and road width. Persaud and Lyon[4] also discussed relationships between collision frequency and vehicle characteristics such as volumes and speeds.

Based on the Swedish model observed by Persaud and Lyon[4], it was determined that 3-legged roundabouts have 8 to 14 percent fewer collisions per million entering vehicles than 4-legged roundabouts. This may indicate that the frequency of collisions at a roundabout may increase with the number of approach legs. If this is true, this could prove to be particularly important at the Asbury Park Circle in the NJDOT Project 2002-16 because this circle contains multiple approach legs, as well as a number of driveways. Reducing the number of driveways and approaches could prove effective in improving the safety of the facility.

The U.K. model discussed by Persaud and Lyon[(4)] looks at the radius of the central island in terms of the relationship between the inscribed circle diameter and the central island diameter. Based on this study, it was shown that as the central island diameter decreases in relation to the inscribed circle diameter accident frequency decreases. This indicates that it is not so much the size of the central island diameter or the inscribed circle diameter that affects the safety of a roundabout. Instead, it is the relationship between the two, referred to as a ratio factor, which impacts the safety of the facility. The ratio factor is equal to:

$$RF = \frac{1}{1-e^{(4R-7)}} \qquad \text{Equation 1}$$

Where, R = inscribed circle diameter/central island diameter.

The Australian model discussed by Persaud and Lyon [(4)] uses the number of lanes as an explanatory variable for the frequency of accidents for rear-end collisions and entering/circulating collisions. Based on these models, the accident frequency will increase with increasing number of lanes on a given approach and on the circulating roadway. This information could prove particularly useful for this project, as the traffic circles are currently unstriped. Although the facilities are wide enough to contain multiple lanes of traffic entering and circulating the facility, striping the facilities to include multiple lanes may in fact increase the number of collisions.

Several observations regarding roadway width were observed in the U.K. models by Persaud and Lyon [(4)]. The first relationship between road width and safety showed that entering/circulating accidents increase with increasing entry width, but decrease with increasing approach width. The second observation showed that approaching accidents decrease with increasing entry width. Although entering/circulating accidents decrease with increasing approach width, the frequency of single vehicle accidents was shown to increase with increasing approach width. Therefore, there will be a trade-off between entering/circulating and single vehicle accidents in relationship to the approach width. However, we can see that reducing entry width may prove to reduce collisions and improve safety at the facilities in this project.

The U.K. model also indicated that approaching and single vehicle accidents would increase as sight distance increases. While this might seem counter intuitive, the reason that this occurs may be due to the correlation between sight distance and speed. The U.K. model contains both sight distance and speed as explanatory variables. However, as sight distance increases, speed will also increase, which would lead to more frequent collisions.

An interesting observation made from the U.K. model is that the model indicates that entering/circulating accidents will decrease as the angle between an arm and the next arm (in a clockwise direction) increases. This indicates that as the angle between arms increases, the entering/circulating conflict becomes similar to that of a merge. This suggests that merging type conflicts will be safer in terms of entering/circulating collisions. One thing to note is that as the angle increases allowing a merge to exist, the speed of entering traffic has the potential to increase. This could lead to an increase in approaching collisions.

Finally, the U.K. model also observes the relationship between collision frequency and curvature, especially entry path curvature. This model shows that entering/circulating accidents will decrease with an increase in entry path curvature, while approaching and single vehicle accidents will increase with increasing entry path curvature. This indicates a trade-off between entering/circulating accidents and approaching and single vehicle accidents in relation to entry path curvature. Therefore, if we want to improve the safety of a facility, we will need to observe the type of collisions that occur more frequently at the facility. The U.K. model also indicates that single vehicle accidents will decrease with increasing severity of right-hand bends on an approach and will increase with increasing severity of left-hand bends on an approach. The Australian model backs up the observations made by the U.K. model, suggesting that single vehicle collisions will decrease as the radius of curvature increases. The Australian model does not include left-hand turns.

Predictive Safety Models

In the Task Report #3 for NYSDOT Project C-01-47, entitled *Operational and Safety Performance of Modern Roundabouts and Other Intersection Types*, a metric for predicting the safety risk at a roundabout was developed by List and Eisenman.[(8)] This metric focuses on the difference in speeds that might exist at various locations. The metric focuses on geometry of a roundabout as the significant cause of speed differences and accidents, and states that the likelihood of an accident can be estimated by examining an aerial photograph.

Figure 1, can be used to explain how the metric works. If we consider the situation where a vehicle enters at A and exits at B (the next leg), the vehicle may not have to slow down if the entry and exit angles are very shallow. This could lead to a safety problem. A similar problem might exist if a vehicle enters at A and exits at C (the next downstream leg). Again, a vehicle may not have to slow down if the inner circle has a small diameter. At a three-leg roundabout, the A-to-B move may be a right-turn or a through depending upon which entry is being considered. If Approach D is absent in the roundabout in Figure 1, then Approach A could have two high-speed possibilities (AB and AC). Approach B could have one (BC), and approach C could have one (CA).

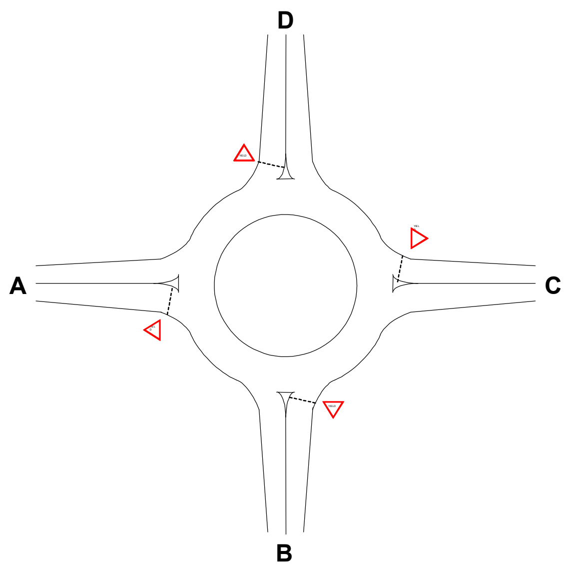


Figure 1. Illustrative roundabout

List and Eisenman[8] suggest that a "number" can be developed that measures the accident-proneness of any site based on the configuration of its legs. It can be written as NN.MM where NN is the number of AC-type approach combinations that can be traversed at high speed and MM is the number of AB-type approach combinations for which high speed is possible. It is important to note that this "number" is not actually a decimal. The decimal point is used to separate the two thoughts. However, the order is important because the metric suggests that the AC-type high-speed moves are likely to cause more accidents than the AB-type moves.

In addition to this metric, Task Report #3 also includes some discussion of a study done for the Insurance Institute for Highway Safety (IIHS). This study was done to determine how safety is impacted by the following variables:

- traffic volumes
- type of control before – signal or stop

- crash history
- number of approaches
- single or multi lane designs
- urban/rural environment
- pedestrian activity

NYSDOT Project C-01-47 used the Bayes method for estimating the impacts of the above variables on safety at roundabouts. This method uses regression analysis to compare before and after accident rates for sites where roundabouts were installed. The formulas used to estimate these rates included the following variables:

F_1 = major road AADT
F_2 = minor road AADT
F_{tot} = total entering AADT

where AADT is equal to the average annual daily traffic flow.

A number of models exist to predict the occurrence of various types of accidents at roundabouts. Maycock and Hall published a document called *Accidents at 4-Arm Roundabouts* in 1984.[(1)] This document contains models that predict accidents of the following types: entering-circulating, approaching, single-vehicle, and pedestrian. All of the models are of the form:

$$A = kQ_a^{\alpha}$$ **Equation 2**

Where, Q represents flow and A is the number of annual accidents on a given approach.

In most cases, Q represents the entering flow, but in the case of entering-circulating accidents, Q_1 is entering flow and Q_2 is circulating flow. In the case of pedestrian collisions, Q is equal to the product of the pedestrian crossing flow and the sum of the entering and exiting vehicular flow. Geometric variables were also included in these models by creating a model of the following format:

$$A = kQ_a^{\alpha} Q_b^{\beta} e^{b_i G_i} \qquad \textbf{Equation 3}$$

where G_i are the geometric variables and b_i are coefficients.

A number of geometric variables were included in the predictive model for each accident type. For entering-circulating collisions, the most important geometric predictor of collisions is the deflection of entering traffic. The three geometric measures of deflection that produced the most statistically significant results were: central island diameter, conflict angle (angle between paths of entering and circulating traffic at the point of crossing) and the maximum entry curvature. The following table shows the variables included in each type of predictive model.

Table 1. Variables included in the predictive models

Accident Type	Variables	Definition
Entering-Circulating	k	Constant
	Q_e	Entering flow
	Q_c	Circulating flow
	C_e	Entry path curvature
	e	Entry width
	ev	Approach width correction
	RF	Ratio factor
	P_m	Percentage of motorcycles
	Θ	Angle between arms
	G	Gradient category
Approaching	k	Constant
	Q	Entering flow
	C_e	Entry path curvature
	$1/V_r$	Reciprocal sight distance
	e	Entry width
	G	Gradient category
Single Vehicle	k	Constant
	Q	Entering flow
	v	Approach width
	C_e	Entry path curvature
	C_{ac}	Approach curvature category
	C_a	Approach curvature (sampled)
	$1/V_r$	Reciprocal Sight Distance
Pedestrian	k	Constant
	Q	(Entering + exiting vehicle flow) x Pedestrian flow

The ratio factor, RF, above is given by 1/(1+exp(4R-7)), where R is equal to inscribed circle diameter/central island diameter.

This study also showed that bicycles account for 13 to16 percent of collisions in roundabouts, and motorcycles account for 30 to 40 percent of collisions in roundabouts. Therefore, two-wheeled vehicles account for 40 to 50 percent of the collisions in a roundabout. Thus, it is important to note the number of bicycles and motorcycles using a facility in order to predict the number of annual collisions.

The FHWA's *Roundabouts: An Informational Guide* also contains predictive models like the ones shown about from Maycock and Hall.(5,1) The variables remain the same, but the variable "A" refers to personal injury collisions per year. Based on this document, it was determined that the following variables have the largest impact on safety at a roundabout: entry width, circulatory width, entry path radius, approach curvature, and angle between entries.

In *Working Paper #2: Safety Models* for NCHRP Project 3-65, Persaud and Lyon discuss predictive safety models for collisions in roundabouts that are currently used in practice in the UK, Australia, and parts of Europe.(4) The United Kingdom models were essentially the models discusses in Maycock and Hall.(1) However, these models were broken down into level 1, level 2, and level 3 models. Level 1 models were models for the total injury accidents for roundabouts of different categories as a whole, as a function of the vehicle and pedestrian flows, where each roundabout contributed one data unit to the analysis.

Level 2 models are those for arm-specific accidents by type, as a function of the vehicle and pedestrian flows, where each roundabout contributed four data units (arms) to each accident type analysis. Level 2 models had the following basic forms:

Accident Type	Accident Prediction Model	
Entering-Circulating	$A = kQ_e^a Q_c^b$	Equation 4
Approaching	$A = kQ_e^a$	Equation 5
Single Vehicle	$A = kQ_e^a$	Equation 6
Other (Non-pedestrian)	$A = kQ_e C^a$	Equation 7
Pedestrian	$A = kQ_{\exp}^a$	Equation 8

The flow functions for these models are shown as follows:

Q_e = entering flow on arm
Q_c = circulating flow across the arm
Q_{ec} = entering * circulating flow on the arm (Q_e*Q_c)
Q_{exp} = (entering + exiting vehicle flow) * Pedestrian flow across arm ((Q_e+Q_x)*P)

where A is the number of injury accidents per year for the entire roundabout, Q is a function of the vehicle and pedestrian flows, and k and a are coefficients to be estimated. The model analysis showed that accidents were more frequent as “small” roundabouts and at high-speed roundabouts.

Level 3 models are similar to Level 2 models except that Level 3 models include geometric variables. The basic form for each accident type was discussed in the

Maycock and Hall[1] section, and is therefore, not discussed again here.

The Australian method discussed in *Working Paper #2* was developed by Owen K. Arndt and was first published in 1994.[4,9] These models estimated the vehicle paths of drivers through roundabouts and the 85th percentile speeds. The output of these models is used to predict single vehicle accidents. In 1998, Arndt published a second document which expanded upon the single vehicle accident models to develop additional models for multiple vehicles and several accident types.[10] Six models were developed and discussed in *Working Paper #2* by Persaud and Lyon: single vehicle accident model, approaching rear-end vehicle accident model, entering/circulating vehicle accident model, exiting/circulating vehicle accident model, sideswipe vehicle accident model, and other vehicle accident model.[4]

Working Paper #2 also covered models developed in Sweden. [4] These models were constructed from data collected at 650 roundabouts in Sweden in 1997. This study showed that accident frequency is directly proportional to vehicle speeds. In addition, injury accident frequency has a quadratic relationship with speed. This study also discussed the safety of roundabouts related to pedestrians and cyclists. Based on observations from 72 roundabouts where pedestrians and cyclists frequently used the facility, single lane roundabouts proved to be safer than multilane roundabouts. It was also found that it was much safer for cyclists to bypass a roundabout on a bicycle crossing than to travel on the carriageway. None of the traffic circles included in the NJDOT Project 2002-16 contain bicycle crossings or indications of how a cyclist should use the facility. Provision of bicycle crossings could improve the safety of these facilities, especially on approaches where bicycle traffic is more frequent.

Conclusions and Recommendations based on Techniques for Evaluating Safety

Based on the information contained in *Accidents at 4-Arm Roundabouts* by Maycock and Hall, *Roundabout Design Guidlines* by Ourston & Doctors, the Austroads *Guide to Traffic Engineering Practice*, *Working Paper #2*: Safety Models from NCHRP Project 3-65 by Persaud and Lyon, and FHWA's *Roundabouts: An Informational Guide*, we can see that the relative velocity between vehicles at conflict points is the most important factor contributing to collisions at a roundabout.[see references 1,2,3,4, and 5] The relative velocity is a function of the geometry of the facility, as well as the speed of a vehicle. The most important geometric factors affecting the relative velocity are entry width, circulating width, entry path radius, approach curvature, and angle between entries. In order to adequately measure and predict level of safety at a traffic circle or roundabout, these variables must be measured for each approach.

As stated above, we wanted to find the relative velocities at points of conflict in the facility. These points of conflict include the merge and diverge sections, as well as weaving sections. In addition, conflicts can occur anywhere that a queue occurs. In the case of the NJDOT Project 2002-16, the queues in the traffic circles were examined to determine points of conflict. Such things as queue length and duration of queue should be taken into account.

From the data collected as part of the NJDOT Project 2002-16, we wanted to extract the velocity at the following points:

- entering the circle from each leg/approach
- exiting the circle from each leg/approach
- circulating within the facility at the point of merge/diverge

This velocity should be a measure of speed and direction so that relative velocities between vehicles may be determined at each point of conflict.

In addition, points of conflict between pedestrians and vehicles, as well as bicycles and vehicles, could be located and analyzed.

Review of Safety Models

Introduction

This chapter is a focused literature review of empirical safety models that are potentially applicable to predicting collisions in traffic circles. Literature has been reviewed dealing with traffic circles, roundabouts and both signalized and unsignalized intersections. There is a Background section followed by a Model Types section where the authors summarize some of the most relevant models for each type of facility and suggestions are made as to which models can be used to validate the safety recommendations for the traffic circles within New Jersey. Next, the section entitled Potential Conflict Evaluation introduces the idea of potential conflicts while the final two sections are where the authors summarize the findings of the models and present recommendations for how to proceed with the safety analysis.

Background

This chapter builds on the previous one, Techniques for Evaluating Safety, and chapter 4 of a masters thesis prepared by Brown (2004) focusing on safety treatments at roundabouts.[(11)] Within that paper, several predictive accident models were discussed that could be used to evaluate the reduction in collisions or risk of collisions created by applying various safety treatments. This paper provides more insight into empirical safety models for traffic circles, roundabouts and standard intersections. As Gettman and Head indicate, "*despite the large body of safety modeling research, absolute numbers of crash and crash rates are still difficult to predict accurately.*" [(12)]

A comprehensive literature search for traffic circle safety models led to no results. The lack of safety modeling for traffic circles could be due to the fact that only a limited number of these facilities exist compared to roundabouts and standard intersections.

Since there were no specific models dealing with traffic circle safety data, roundabout safety models were analyzed. Although there are similarities between the two types of facilities there are some dramatic differences as well. One of the most notable is that the yield control for a traffic circle is located within the circle (on the circulating roadway).

The largest percentage of safety performance research has been done with respect to unsignalized and signalized intersections. Although some of these studies may contain valuable information regarding safety performance it is difficult to utilize the thoughts within the realm of traffic circles. Of the two types of facilities, signalized intersection research is least likely to contain information useful for modeling the safety of traffic circles.

Signalized intersections are entirely controlled. Therefore, the way motorists perceive these facilities is distinctly different than that of traffic circles. Key issues associated with this thought include the visibility of the signal heads, lane assignments and operational rules. Also, because of the control type, vehicular flow patterns are a constant bimodal flow pattern (stop and go). This phenomena yields specific accident types in differing proportions from those of a traffic circle, like rear-end collisions. The geometry of a standard intersection is typically much more “right angle” in nature. Therefore, head-on and left-turn accidents are common, as is not the case with traffic circles and roundabouts. Lastly, drivers from the United States are trained from an early age how to interact safely in standard right angle intersections because they are commonplace in our networks, unlike traffic circles and roundabouts which are quite rare.

Although unsignalized intersections more closely align with traffic circles than do signalized intersections due to the control type, there are still dramatic differences between the facilities. Similar to signalized intersections, there are considerable geometric differences compared to traffic circles.

Model Types

Within this section of the report there is a comprehensive discussion pertaining to specific safety models that have been applied to roundabouts and signalized and unsignalized intersections. Based on these reviews, the study team was able to select the most appropriate models that pertain to the traffic circles being studied as part of this project.

Roundabout Safety Models

At the present time there are no U.S.-specific roundabout safety models. Rather they have been adapted from the primary models developed for the UK, Australia and Sweden.(see references 1,2,3,4,5,6,7,8,9 and 10.) FHWA has produced *Roundabouts: An Informational Guide*, which has an entire chapter devoted to describing various roundabout safety models that may be used for comparative purposes within the United States.[5] The major models are now discussed.

MAYCOCK & HALL – UK MODEL (1984)[1]

Maycock and Hall (1984) found that accident frequencies by type at roundabouts could be predicted by linear regression models.[1] The model they developed was based on data from UK roundabouts. This model is capable of predicting the following accident types at four-legged roundabouts:

1) accidents between entering and circulating vehicles
2) approaching accidents (mainly rear-end collisions but also lane changing accidents)
3) single vehicle accidents
4) other vehicle-to-vehicle accidents
5) pedestrian-vehicle accidents

Maycock and Hall estimated three levels of models, consisting of:

Level 1: Models for total injury accidents for roundabouts of different categories as a whole, as a function of the vehicle and pedestrian flows, where each roundabout contributed one data unit to the analysis.

Level 2: Models for arm-specific accidents by type, as a function of the vehicle and pedestrian flows, where each roundabout contributed four data units (i.e. arms) to each accident type analysis.

Level 3: Similar to Level 2 but with geometric variables added.

Level 1 Model

The basic form of this model is:

$$A = kQ_a^{\alpha}$$

where,

A	is accidents per year for the entire roundabout,
Q	is a function of the vehicle and pedestrian flow movements at the roundabout (all 24 hour annual average flows in thousands of vehicles),
k, *a*	are parameters to be estimated.

Level 2 Model

For level 2 and 3 models each arm of the roundabout was used as the basic unit of analysis. Since level 2 models are virtually the same as level 3 models with the exception of no specific geometric variables the discussion of these models can be seen in the discussion for level 3 models.

Level 3 Model

This version of Maycock and Hall's (1984) model includes geometric and other site-specific variables. Although there are no U.S.-specific roundabout crash prediction models the FHWA Roundabouts Informational Guide presents this model and cautions the user that it can be used as for comparative purposes within the U.S.[5] The basic form of the model is represented as:

$$A = kQ_a^{\alpha} Q_b^{\beta} e^{b_i G_i}$$ Equation 3

where,

A	is the accident frequency (accidents / year) assigned to a roundabout arm,
Q_a, Q_b	are an annual average daily flow which depends on accident type,
G_i	continuous variables, e.g. flow proportions, geometric variables,
b_i	is the coefficient for G_i
k, α, β	are constants which depend on accident type.

The parameters and geometric predictions are shown in Table 2.

Table 2. Equations for accident frequency prediction at roundabouts [4,6]

Accident Type	Q	K	α	β	b_i	G_i
1)	-	0.052	0.7	0.4	-40	C_e, entry curvature
					0.14	e, entry width
					-0.007	e and v, approach width correction
					-0.01	θ, angle between arm
					0.2	P_m (percentage motorcylces)
					-1	Ratio Factor, RF - 1/(1+exp(4R-7)) and R=D/CID
2)	Q_e	0.0057	1.7	-	20	C_e
					-0.1	e
3)	Q_e	0.0064	0.8	-	25	C_e
					0.2	v
					-45	C_a, approach curvature
4)	Q_e, Q_c	0.0026	0.8	-	0.2	P_m
5)	$Q_p(Q_e + Q_{ex})$	0.029	0.5	-	-	

Table 2 represents the parameters that Maycock and Hall found to be most applicable for their model. The FHWA Guide and Semmens (1985) also make use of the variables and define each of the geometric parameters (G_i).[4, 6] According to this crash model, the major physical factors that were statistically significant are entry width, circulatory width, entry path radius, approach curvature and angle between entries.[4]

ARNDT'S MODEL – AUSTRALIAN MODEL (1998)

The FHWA roundabout guide presents the Australian model developed by Arndt.[4] The first model developed in 1994 builds off of a collection of accident, traffic and geometric data for Australian roundabouts.[9] In 1998, Arndt revised his initial model to include several accident types and both linear and non-linear Poisson based regression models were adapted. This model is capable of predicting the following accident types:

1) single vehicle accidents
2) approaching rear-end vehicle accidents
3) entering / circulating vehicle accidents
4) exiting / circulating vehicle accidents
5) sideswipe vehicle accidents
6) other vehicle accidents

The model is sensitive to the paths followed by the vehicles and 85th percentile speeds. These pieces of information are plugged into a regression model along with other significant predictors of accidents, resulting in an estimate of accident frequency.[10] The significant difference between this model and Maycock and Hall (1984) is that the independent variables are derived from driver behavior.[1] One can note that all of Arndt's accident type models are of the same general form:

$$A = \text{constant} * Q^{\text{constant}} * f\,(S, \text{other variables}) \quad \textbf{Equation 9}$$

All of the models yield an annual accident rate through a constant multiplied by the flow raised to a constant multiplied by a function of the speed (S) and one or more variables. Below are detailed descriptions of the individual models.

SINGLE VEHICLE ACCIDENT MODEL

The basic form of this model is as follows:

$$A_{sp} = 1.64 \times 10^{-12} Q^{1.17} L \frac{(S+\Delta S)^{4.12}}{R^{1.91}} \quad \textbf{Equation 10}$$

$$A_{sa} = 1.79 \times 10^{-9} Q^{0.91} L \frac{(S+\Delta S)^{1.93}}{R^{0.65}} \quad \textbf{Equation 11}$$

where,

A_{sp}	is the number of single vehicle accidents per year per leg for vehicle path segments prior to the "give way" line
A_{sa}	is the number of single vehicle accidents per year per leg for vehicle path segments after the "give way" line
Q	AADT in direction consideration
L	length of vehicle path on the horizontal geometric element (m)
S	85th percentile speed on the horizontal geometric element (km/hr)
ΔS	decrease in 85th percentile speed at the start of the horizontal geometric element (km/hr)
R	vehicle path radius on the horizontal geometric element (m)

It should be noted that this model only applies for vehicles making right and U-turns, not left turns.

APPROACHING REAR-END VEHICLE ACCIDENT MODEL

The basic form of this model is as follows:

$$A_r = 1.81 \times 10^{-18} Q_a^{1.39} (SQ_{ci})^{0.65} S_a^{4.77} N_a^{2.31} \quad \textbf{Equation 12}$$

where,

A_r	is the number of approaching rear-end vehicle accidents per year per approach leg
Q_a	approach AADT
Q_{ci}	AADT from circulating roadway (other approaches)
S_a	85th percentile speed on the approach curve (km/hr)

N_a	number of lanes on the approach

ENTERING / CIRCULATING VEHICLE ACCIDENT MODEL

This model is used to estimate conflicts between entering and circulating vehicles. The basic form of this model is as follows:

$$A_e = 7.31 \times 10^{-7} Q_a^{0.47} N_c^{0.9} (SQ_{ci})^{0.41} S_{ra}^{1.38} / t_{Ga}^{0.21} \quad \textbf{Equation 13}$$

where,

A_e	is the number of entering/circulating vehicle accidents per year per approach leg
Q_a	approach AADT
N_c	number of circulating lanes
SQ_{ci}	sum of circulating vehicle AADT's from the other approaches
S_{ra}	$(SQ_{ci} \times S_{ri}) / SQ_{ci}$
t_{Ga}	$(SQ_{ci} \times t_{Gi}) / SQ_{ci}$
S_{ri}	relative 85th percentile speeds between vehicles on the approach curve and circulating vehicles from each direction (km/hr)
t_{Gi}	$3.6 \times d_{Gi} / S_{ci}$
d_{Gi}	distance from give way line of the approach to the intersecting point between entering / circulating vehicles
S_{ci}	85th percentile speeds of circulating vehicles adjacent to the approach (km/hr)

EXITING / CIRCULATING VEHICLE ACCIDENT MODEL

This model is used to estimate accidents between exiting and circulating vehicles at an Australian roundabout. The general form of the model is represented as:

$$A_d = 1.33 \times 10^{-11} (SQ_{ci})^{0.32} (SQ_{ei})^{0.68} S_{ra}^{4.13} \quad \textbf{Equation 14}$$

where,

A_{ss}	number of exiting / circulating vehicle accidents per year per existing approach
SQ_{ci}	sum of circulating vehicle AADT's from the other approaches

SQ_{ei}	sum of various AADT flows exiting the roundabout at the exit point of the departure leg
S_{ra}	$(SQ_{ei} \times S_{ri}) / SQ_{ei}$
S_{ri}	85th percentile speeds between vehicles exiting the roundabout and circulating vehicles at the departure leg

SIDESWIPE VEHICLE ACCIDENT MODEL

This model is used to estimate *sideswipe accidents* at Australian roundabouts. The general form of the model is represented as:

$$A_{ss} = 6.49 \times 10^{-8} \ (Q^*Q_t)^{0.72} \Delta f^{1.59}$$ **Equation 15**

where,

A_{ss}	number of sideswipe accidents per leg per vehicle path segment
Q	AADT for the particular movement on the geometric element of interest
Q_t	total AADT on the geometric element of interest
Δf_1	difference in potential side friction (km/hr^2/m)

OTHER VEHICLE ACCIDENT MODEL

This model is used to estimate *other accidents* at Australian roundabouts. The general form of the model is represented as:

$$A_0 = 4.29 \times 10^{-6} (SQ_a)$$ **Equation 16**

where,

A_0	number of other accidents per year
Q_a	AADT on approach a

BRUDE AND LARSSON - SWEDISH MODEL (1997)

In 1997, Brude and Larsson analyzed approximately 650 roundabouts in

Sweden. Based on their findings they were able to develop two variants of prediction models for Swedish roundabouts.[24] As a result of this model one of the conclusions reached by the study was that accident frequency is directly proportional to vehicle speeds.

VARIANT 1

The general form of the first variant is represented as:

$$A_P = 0.1253 x 0.86^{3\ leg} x 1.88^{speed70} x 1.2^{2lanes}$$ **Equation 17**

where,

A_P	predicted accident rate
3 leg	is 1 if 3 leg roundabout, or 0 if 4 leg roundabout
Speed70	is 1 if speed limit is 70km/hr, or 0 if 50 km/hr
2lanes	is 1 if there are 2 lanes on the roundabout, or 0 if there is 1 lane

VARIANT 2

The general form of the second variant is represented as:

$$A_P = 0.1130 x 0.92^{3\ leg} x 1.84^{speed70} x 1.4^{loclow} x 1.17^{2\ lanes}$$ **Equation 18**

where,

3 leg	is 1 if 3 leg roundabout, or 0 if 4 leg roundabout
Speed70	is 1 if speed limit is 70 km/hr, or 0 if 50 km/hr
Loclow	is 1 if speed limit is within 600m of roundabout is higher than the local limit
2lanes	is 1 if there are 2 lanes on the roundabout, or 0 if there is 1 lane

FRENCH MODEL (1997)

This model has been proposed by the French to predict accidents at roundabouts.[25] The structure of the model is as follows:

$$A = 0.15 \times 10^4 \times T_e$$ **Equation 19**

or

$$A = 0.24 \times 10^6 \times T_e^{1.4}$$ Equation 20

where,

T_e daily traffic in the roundabout

Signalized and Unsignalized Intersection Safety Models

The analysis of signalized intersections is much more common in the United States than traffic circles or roundabouts. The FHWA produced the *Signalized Intersections: Informational Guide*, to assist with the design of this type of facility.[14] Signalized intersection safety models tend to produce results dealing with head on and right angle collisions, both of which are extremely rare within traffic circles.

The paper written by Persaud and Musci entitled *Microscopic Accident Potential Models for Two-Lane Rural Roads* describes how intersection data from Ontario, Canada was used to predict accidents at standard intersections.[15] Using the data in simple model form and a regression package the assumption of a negative binomial error structure could be used to calibrate different combinations of time and geometric characteristics. Mehmood, Saccomanno and Hellinga have developed a system dynamics model for simulating road crashes.[16] The model used is applied to two vehicle rear-end crashes where both vehicles are assumed to be traveling in the same lane. The model extends the classical car-following theory in combination with crash avoidance models.

Simulation of Traffic Conflicts at Unsignalized Insersections with TSC-Sim, by Sayed et al., describes a traffic conflict computer simulation model and graphical display for both a "T" and a four-leg unsignalized intersection. The goal of the model is to study traffic conflicts as critical event traffic situations and the effect of driver and traffic parameters on the occurrence of conflicts.(17) Salman and Al-Maita perform safety evaluations at a three legged unsignalized intersections by using traffic conflict techniques. Linear regression is used to perform this evaluation.(18)

MODEL 1

A typical practice to evaluate a standard intersection is to compute the crash rate per million entering vehicles (*RMEV*). In order to compute this it is necessary to have the number of crashes in a given year and the ADT on all approaches of the intersection. Fricker presents formula for determining the *RMEV* is as follows:(19)

$$RMEV = \frac{(Crashes / year)}{(approach\ ADT \times days / year)} \times 10^6 \qquad \text{Equation 21}$$

When determining the number of crashes prevented the following equation may be used:

$$Crashes\ \Pr evented = EC \times CRF \times (\frac{forcast\ \mathrm{ADT})}{(Base\ ADT)} \qquad \text{Equation 22}$$

where,

EC	expected number of crashes over a specified time
CRF	crash reduction factor, which is the percent reduction in crashes if a countermeasure is implemented

MODEL 2

Traffic Safety Software, LLC, has created a microscopic traffic accident prediction software package called TRAF-Safe. This package is capable of estimating the number of annual accidents and injury accidents for any typical highway intersection or roundabout. Software validation yielded an accuracy of over 70 percent for unsignalized intersections and over 80 percent for signalized intersections.[20] For standard intersections the basic model presented for analyzing angle and rear-end collisions is represented as:

$$PCO\,(Conflict\,Type)_t = E(Movement\,Opportunities)_{i\,j} \times P(ArrivalofOppositiontoMovement)_{k\,l}$$

Equation 23

where,

PCO	Probable Conflict Opportunity
t	specific conflict type
i	arrival movement type
j	arrival approach
k	opposition movement type
l	opposition approach

$E(Movement\ Opportunities)_{ij}$	expected number of vehicles per unit time for a specific movement type "*i*" which may be exposed to an opposition movement on any particular roadway segment or intersection approach
$P(Arrival\ of\ Opposition\ to\ Movement)_{kl}$	for angle and rear-end accidents the probability of arrival of one or more vehicles during the specific time period of exposure to a particular type of conflict "*k*" on any particular roadway segment or intersection approach or adjacent lane "*l*" where using the Poisson Distribution

Similar models exist for sideswipe merge and weave events and fixed object / single vehicle accidents. The model that is presented for roundabouts is similar to the standard intersection models, with major assumptions being made. One of the key assumptions is that roundabouts are essentially multi-leg standard intersections with yield control rather than stop control.[20]

Potential Conflict Evaluation

Although the bulk of this paper discusses models aimed at estimating accidents within a facility, this section deals with evaluating potential conflicts. *A conflict is defined as an observable situation in which two or more road users approach each other in time and space for such an extent that there is a risk of collision if their movements remain unchanged.*[21]

Several studies have been conducted pertaining to the evaluation of potential conflicts.[22,23] Mauro and Cattani propose a model capable of evaluating potential conflicts at roundabouts.[23] The basis for the idea is driven by the thought that for an incident to occur, other vehicles must be situated so that the accident can occur. For example, a rear-end collision will occur with an approaching vehicle if there is a vehicle waiting to enter a facility. This paper presents the models for determining the potential conflicts per unit of time for several types of crashes.

Although evaluating potential conflicts is not part of the scope of this project it would be of great importance to pursue additional research to modify the PARAMICS software to model this phenomena.

Summary of Models & Applicability

Based on this review of the various types of empirical safety models it has been found that no specific models for traffic circles have been developed. There has been a considerable amount of work done abroad related to roundabouts. However, no United States specific models have been developed. The roundabout guide produced by FHWA presents the U.K. and Australian models to be used for comparative purposes within the U.S.[5] The other roundabout models do not fully consider the geometric design of the facility, rather they tend to focus strictly on the traffic volumes at the facility.

Safety models pertaining to standard signalized and unsignalized intersections were also studied. These models tend to be less geometrically constrained than roundabout models and deal primarily with AADT's.

The accident types at traffic circles more closely align with those at roundabouts than at standard intersections. At standard intersections there is a high probability for head-on and right angle collisions, these events seldom occur at traffic circles and roundabouts.

Table 3. Summary of reviewed models

Model	Facility				Accident Type							Applicability	Reference
	Traffic Circle	Roundabout	Unsignalized	Signalized	Single Vehicle	Rear-end	Right Angle	Side-Swipe	Head On	Total Accidents	Other		
UK Roundabout Model (1984)		X			X	X		X			X	High	(5)
Australian Roundabout Model (1998)		X			X	X		X			X	High	(8)
Swedish Roundabout Model (1997)		X								X		Mid	(9)
French Roundabout Model (1997)		X								X		Low	(10)
Standard Intersection Model			X	X		X	X	X	X			Low	(11)
System Dynamics Models			X	X						X		None	(13)
General Purpose Simulation System			X							X		None	(14)
Traffic Conflict Technique			X							X		None	(15)
Empirical Bayesian Approach for Rural Roads			X	X						X		None	(16)
Microscopic Accident Prediction Model (1993)		X	X	X		X	X		X			Low	(17)

Empirical Model Recommendations

As part of this project it is necessary to validate the PARAMICS results that have been produced. This can be done by choosing an empirical safety model that has similar characteristics of the traffic circles. After thoroughly examining all of the possible empirical safety models it is recommended that only the safety models for roundabouts should be analyzed.

Although an exact prediction of accidents is not expected, it is anticipated that the accident models for roundabouts will more closely align with traffic circles than the models for standard intersections. Rather than just choose a single model, several models were employed to ensure that the traffic circle results are similar for each model. Both the U.K. model by Maycock and Hall (1984) and Australian model by Arndt (1998) have geometric attributes that can be used for the New Jersey traffic circles of interest. [1,10] Also, each of these models can be modified to reflect each of the different accident types that may occur within a traffic circle.

Safety Treatments

Introduction

This chapter provides an overview of typical procedures used to perform a safety evaluation. In addition, it discusses safety treatments that are currently in practice or are recommended at roundabouts and traffic circles. Some discussion of the safety problems that exist at the three traffic circles, based on accident histories, included in NJDOT Project 2002-16 is also included in this section. Finally, this section discusses some of the safety treatments that were used in the PARAMICS modeling process part of the project.

This chapter begins with a discussion of safety treatments that have been tried and/or are recommended to improve safety conditions at traffic circles. Following this discussion is an overview of the steps involved in performing a proper safety analysis of an intersection or roadway as outlined in the *Road Safety Good Practice Guide* published by the Department for Transport.[(26)]

Safety Treatments

A technique used for making safety improvements in Great Britain and discussed in the *Road Safety Good Practice Guide*, is known as black spot treatment.[(26)] This technique involves applying low cost treatments to clusters of accidents with a common factor. In order to apply this technique, one must first identify high accident locations and then identify commonalities in the causes of the collisions. Once the major causes have been identified, a low cost solution can be applied to reduce these collisions. In the sections below, several factors that affect accident rates are examined. In addition, some solutions to these safety issues are given.

Speed and Relative Velocity

According to the *Road Safety Good Practice Guide*, the single most important factor in improving safety is reducing speeds.[26] The guide states that lowering speeds, especially in urban areas, will prove to be a benefit to all road users and particularly to pedestrians and cyclists. In Great Britain, nearly two thirds of drivers exceed 30 mph in areas where this is the posted speed limit. Therefore, reducing average speeds can prove to be a large benefit to safety.

It should be noted that reduction of average speeds would not occur by reducing the speeds of all road users. Instead, the goal should be to reduce the speeds of the fastest road users. It has been shown that these drivers possess the greatest risk for collision. Therefore, they should be the targets in improving safety conditions in terms of speed.

According to Taylor in “Vehicle Speed Distributions and Safety on Urban Roads,” safety treatments designed to reduce speed should attempt to achieve a safe distribution of speeds on roads according to the function of the road.[30] In other words, a safe freeway would have a speed distribution of something similar to 50-65 mph. However, a road in a residential area near a school would have a speed distribution between 15-25 mph. Taylor suggests that the average speed on a roadway should be appropriate to the prevailing conditions on that roadway. In addition, Taylor notes that all vehicles on the roadway should be moving at a speed as close as possible to the average speed on the roadway.

This idea mentioned by Taylor is similar to the point that was made in earlier sections of this report. As discussed in this document, the relative speeds or velocities of vehicles at traffic circles, especially at entrance and exit locations, is a major factor affecting safety. Whenever possible, we want to reduce the relative velocities of vehicles. This does not necessarily mean reducing the average speed of vehicles. Instead, it refers to applying treatments that force drivers to travel at speeds very close to the average speed.

Reducing relative vehicle velocities can be done by two methods. The first method is to apply safety treatments that force entering, circulating, and exiting vehicles to travel at very similar speeds. These speeds do not necessarily have to be reduced. Rather they should be made more equal.

The second method for reducing relative vehicle velocity is to reduce the angle between vehicles while entering, circulating, and exiting the traffic circle. This would be achieved through geometric modifications to the traffic circle. This type of treatment would allow vehicles to enter and exit the traffic circle on a more tangential path. Evidence has proven that entry on a tangential path often leads to increase entry speeds, especially where the entering traffic has the right-of-way. Therefore, reducing the angle between entering and circulating vehicles may not be the most appropriate safety treatment. There is no greater proof for this than in modern roundabouts where the entry angle is often exaggerated to create greater deflection upon entry.

Ourston & Doctors' *Roundabout Design Guidelines* contains a chapter on safety, which discusses the significance of entry speed at roundabouts, as well as ways to reduce accidents at these facilities.(2) This document lists excessive speed as the most common problem affecting safety at roundabouts. Two of the major factors that contribute to such high speeds are inadequate entry deflection and an acute entry angle, which encourages fast merging, maneuvers with circulating traffic. Currently these two factors are large contributors to collisions at the Collingwood and Asbury Park traffic circles where relatively low entry deflection exists and merges take place at speeds near 45 mph. Increasing the entry deflection and the entry angle could prove beneficial in reducing collisions at both of these traffic circles.

Ourston and Doctors also point out that high circulatory speeds can cause entry problems, and therefore, significant safety issues.[2] This is a particularly significant problem at large roundabouts with excessively long or wide circulatory roadways. This could prove to be an issue particularly at the Asbury Park and Collingwood Circles, because they are rather large facilities. In addition, Asbury Park has wide and long circulatory roadways that are not currently striped, allowing vehicles to travel at higher speeds.

Taylor notes in "The Effects of Drivers Speed on the Frequency of Road Accidents" that the differential between the speed limits inside and outside a village can be large.[29] While none of the traffic circles in NJDOT Project 2002-16 are located in villages, they are located in town centers where traffic tends to be moving at higher speeds further away from the traffic circle. Taylor points out that if drivers have been traveling along rural roads subject to higher speed limits for an appreciable distance, they may not recognize the need for greater care and lower speeds when they enter a village, or town center. They may be unaware of a lower speed limit or of their own speed and may respond late to the lower limit. In particular they may be unaware of the increased risk of an accident, especially with a vulnerable road user. According to Taylor's studies, speeds observed through villages are often high compared to what is appropriate for the conditions. Asbury Park and Collingwood Circles are both in areas where traffic tends to be traveling very quickly on roads entering the circle. The geometry of these circles does not require that drivers slow down upon entering the circle, or that they recognize that they have entered a circle at all. Therefore, care should be taken to ensure drivers recognize the change in environment and roadway conditions. Taylor suggests the use of advance signage and narrowing of the roadway to alert drivers to the change in speed.

The *Florida Roundabout Guide* gives a set of standards that define a roundabout.[27] One of these standards is that the speed at which vehicles are able to travel should be controlled by the location of the central island with respect to the alignment of the right entry curb. This feature of roundabouts is listed as a key feature giving improved safety to roundabouts over traffic circles. The speed in the traffic circles included in NJDOT Project 2002-16 is controlled largely by the speed limits at the facilities. In addition, the requirement for vehicles circulating the facility to yield to entering vehicles reduces the speed of circulating vehicles. However, there is no such requirement for exiting vehicles to reduce speed while navigating the facility. This creates a large speed differential between entering and circulating, and circulating and exiting vehicles. Using geometry changes to reduce speeds at these traffic circles may prove effective in improving safety. The *Florida Roundabout Guide* points out that many large traffic circles, such as Asbury Park, provide straight paths for the major movements and are often designed for higher speeds within the circulating roadway.(27) These design features, intended to improve capacity, can also lead to reduced safety.

Angle Between Entering Roads

A factor that Ourston and Doctors list as a leading cause of accidents at roundabouts is an insufficient angle between entering roads.(2) The likelihood of entry accidents is dependent on the counterclockwise angle between an approach leg and the next approach leg, as well as the counterclockwise angle between an approach leg and circulating traffic flow. According to Ourston and Doctors, approaches with high entry flows should have large angles to the next entry.(2) The reverse is true for approaches with lower entry flows.

This point is backed up in the U.K. model contained in *Accidents at 4-Arm Roundabouts* by Maycock and Hall.(1) This model indicates that entering/circulating accidents will decrease as the angle between an arm and the next arm (in a clockwise direction) increases. This indicates that as the angle between arms increases, the entering/circulating conflict becomes similar to that of a merge. This suggests that merging type conflicts are safer in terms of entering/circulating collisions. One thing to note is that as the angle increases allowing a merge to exist, the speed of entering traffic has the potential to increase. This could lead to increase approaching collisions.

Particularly at the Asbury Park traffic circle, the angle between an approach leg and the next approach leg is rather small. The elongated shape of the outer circle in Asbury Park places the approach legs at either end of the circle at less than a 45-degree angle from each other. This forces vehicles entering at one approach and exiting at the next to make a nearly 180 degree turn on a rather short roadway segment. It also forces vehicles entering at one approach and exiting at the next to travel at very low speeds compared to vehicles circulating the traffic circle at this point. As was mentioned above, this large difference in the relative speeds of vehicles entering, exiting, and circulating can lead to greater numbers of and more severe accidents.

Entry Deflection

Austroads' *Guide to Traffic Engineering Practice* includes a section on roundabouts.[3] It contains only a very small section related specifically to safety, but discusses factors such as speed control and deflection, sight distances, superelevation and drainage, pedestrians and bicycles, line marking and striping, and proper lighting, and how these affect safety and operations in roundabouts. According to Austroads, the deflection of vehicle paths entering a roundabout is the most important factor affecting safety. This deflection can be achieved by adjusting the geometry of the entry or ensuring that vehicles going straight through the facility are deflected by one of the following methods: alignment of the entry and shape, size and position of the splitter islands; placement and size of central island; or use of a staggered or non-parallel alignment between any entry and exit.

Roadway Width

In *Accidents at 4-Arm Roundabouts*, Maycock and Hall discuss predictive safety models that were developed in the U.K., Australia, and Sweden.[(1)] Based on these models, Maycock and Hall were able to determine relationships between collisions and geometric characteristics of roundabouts such as number of approaches, radius of central island, number of lanes and road width.

Several observations regarding roadway width were observed in the U.K. models by Maycock and Hall. The first relationship between road width and safety showed that entering/circulating accidents increase with increasing entry width, but decrease with increasing approach width. The second observation showed that approaching accidents decrease with increasing entry width. Although entering/circulating accidents decrease with increasing approach width, the frequency of single vehicle accidents was shown to increase with increasing approach width. Therefore, there is a trade-off between entering/circulating and single vehicle accidents in relationship to the approach width. However, we can see that reducing entry width may prove to reduce collisions and improve safety at the facilities in NJDOT Project 2002-16.

Curvature

The U.K. model contained in *Accidents at 4-Arm Roundabouts* also observes the relationship between collision frequency and curvature, especially entry path curvature.[(1)] This model shows that entering/circulating accidents will decrease with an increase in entry path curvature, while approaching and single vehicle accidents will increase with increasing entry path curvature. This indicates a trade-off between entering/circulating accidents and approaching and single vehicle accidents in relation to entry path curvature. Therefore, if we want to improve the safety of a facility, we will need to observe the type of collisions that occur more frequently at the facility. The U.K. model also indicates that single vehicle accidents will decrease with increasing severity of right-hand bends on an approach and will increase with increasing severity of left-hand bends on an approach. The Australian model backs up the observations made by the U.K. model, suggesting that single vehicle collisions will decrease as the radius of curvature increases.

Sight Distance

According to the *Road Safety Good Practice Guide*, problems can arise at uncontrolled junctions if there is any obstruction to drivers visibility.(26) For example, this could be due to the building line, vegetation, parked vehicles or overtaking vehicles being masked by the vehicles being overtaken. It is important that all road users have adequate visibility in each direction at a junction. This allows them to judge approaching traffic and to complete their maneuver with sufficient margins of safety. Proper visibility is especially important for pedestrians and cyclists.

The U.K. model included in *Accidents at 4-Arm Roundabouts* also indicated that approaching and single vehicle accidents will increase as sight distance increases.(1) While this might seem counter intuitive, the reason that this occurs may be due to the correlation between sight distance and speed. The U.K. model contains both sight distance and speed as explanatory variables. However, as sight distance increases, speed will also increase, which would lead to more frequent collisions.

The *Road Safety Good Practice Guide* notes that collision problems can occur at junctions where the road ahead is more visible than the junction itself to approaching vehicles.(26) This is particularly a problem where approaching vehicles must yield to traffic in the junction. Therefore, proper sight distance must be provided to approaching vehicles. In addition, proper entry curvature should be provided, requiring approaching vehicles to reduce speed while entering the junction.

Pedestrians and Cyclists

According to *Road Safety Good Practice Guide*, the presence of pedestrians and cyclists near the junction can often generate accidents.(26) Therefore, special consideration needs to be given to these road users. Whenever possible and practical, separate routes for pedestrians and cyclists are generally recommended to be away from the junction where vehicle movements are more predictable. Ideally, pedestrians and cyclists should cross where the road width can be minimized. In addition, the installation of refuges where pedestrians normally choose to cross has been found to provide safety benefits. Such a refugee should accomplish the following:

- reduce the number of streams of traffic in which pedestrians need to decide when it is safe to cross
- minimize the distance over which pedestrians are exposed to traffic
- provide safe central areas

The *Road Safety Good Practice Guide* also notes that pedestrians tend to minimize their walking distance and will, therefore, cross major roads where it is convenient to do so and not always where it is safest.(26) The guide recommends that the safest policy is normally to minimize conflict points between vehicles and pedestrians so that driver attention can be focused at designated controlled crossing places. This also involves taking the steps above to provide safe crossing for pedestrians and cyclists.

A solution to the pedestrian and cyclist problem given in the *Road Safety Good Practice Guide*, is to place guard rails or fencing to channel pedestrians to the designated crossings.(26) However, these devices have a number of disadvantages. They are visually unappealing, reduce walkway width, can obscure children, and can create difficulties accessing commercial properties. Therefore, these devices should only be considered where the risks of walking on the roadway are very high.

Currently, cyclists must navigate through the traffic circles in NJDOT Project 2002-16 by using the circulating roadway. However, a study performed by the Swedish National Road and Transport Research Institute showed that cyclists are at nearly 3.5 times greater risk of being involved in a collision when using the roadway to traverse a roundabout than when using bicycle crossings.[(24)] Therefore, in order to improve the safety of the traffic circles for cyclists, bicycle crossings should be provided at appropriate locations, removing bicycles from the circulating traffic. One of the reasons that using the circulating roadway can be so dangerous for cyclists is that they are often not visible to other vehicles and can easily be obscured by large trucks or overtaking vehicles. In addition, cyclists are not able to easily view surrounding traffic in order to predict how another vehicle may navigate the facility.

According to the study performed by the Swedish National Road and Transport Research Institute, bicycle crossings are safest when placed 2-5 m from the entry point.[(24)] This type of design is favorable because it allows traffic to enter the roundabout in two stages. In the first stage, entering drivers may pay attention to cyclists attempting to cross the roadway. In the second stage, drivers may pay attention to circulating traffic and will have sufficient area to yield to circulating vehicles without obstructing the bicycle crossing.

Signage

Many of the treatments that have been proven to reduce accidents at roundabouts are related to signage. The repositioning of signs can significantly improve the safety of a facility. In addition, map-type signs placed in advance of the facility can also improve safety. Some other signage treatments include: making the yield line more conspicuous; moving the central island chevron sign further to the right to emphasize the angle of turn; placing an additional chevron sign above the normal position; and placing chevron signs in the median in line with the left lane approach on divided roads. Ourston and Doctors also suggest the use of “Reduce speed now” signs or count down markers, especially on high-speed approaches.(2)

While signage changes may prove to benefit safety conditions at the traffic circles in NJDOT Project 2002-16, it should be noted that the cost-benefit analysis for this project was performed using the PARAMICS software package. This program is not capable of modeling the changes in driver behavior by adding or changing signage. Therefore, there was no way of measuring the impacts of such improvements. For this reason, it is unlikely that signage changes will be recommended for this experimental project to be included in the cost-benefit analysis.

According to statistics included in the British *Traffic Signs Manual* (TSM), 54 percent of accidents occurring at junctions in the U.K. occur at roundabouts.(31) Many of the problems at other junctions are a consequence of drivers’ difficulty in judging the speed and distance of other traffic. Due to these statistics, the TSM contains suggestions for improving safety at such junctions.(31) It notes that the approaches to junctions should be adequately and clearly signed. Such signing should be map-like in nature, allowing drivers to easily determine how they should maneuver the junction. In addition, the TSM recommends the provision of anti-skid surfacing on the approach to the junction to reduce the risk of collisions, especially rear-end collisions. The TSM further notes that junctions and the traffic within the junction should be conspicuous and drivers should have adequate warning to slow down and be aware of the path they should take through the junction. In addition, priorities should be made clear. On high speed approaches where little visual stimulation is provided in advance of the roundabout, the provision of yellow bar markings on the approaches is one option for giving drivers advance warning of the junction. On larger roundabouts, lane markings may help guide drivers through the junction. While such lane marking is often not recommended and is highly controversial in the United States, lane markings have been proven effective in the U.K. where drivers tend to understand the rules of traversing a roundabout.

Striping

According to the British TSM, following distances are particularly important where forward visibility is restricted.[31] The curves of a roundabout can often inhibit visibility. The problem can be made worse by a wide roadway, which may encourage staggered following behavior with shorter following distances. In order to reduce this problem, the TSM recommends the use of white line striping about 1m or more from the edge of the road or continuous center hatching to reduce the effective carriageway width to approximately 7m to reduce accidents.

Chapter 7 of the FHWA's *Roundabouts: An Informational Guide* contains a section on pavement markings at roundabouts based on guidelines set forth in the latest version of the *Manual on Uniform Traffic Control Devices* (MUTCD).[5,6] This document suggests that yield lines should be located along the inscribed circle to mark the entry approach. These yield lines should be broken lines consisting of 400-mm wide stripes with 1-m segments and 1-m gaps. No yield lines should be used to mark the exit from the circulating roadway. This guideline is set forth for roundabouts in which the traffic entering the circle must yield to the circulating traffic. However, the facilities considered for NJDOT Project 2002-16 are traffic circles in which the circulating traffic must yield to the entering traffic. The FHWA also suggests that triangle shaped white markings can also be used to mark the yield line, as is done in parts of Europe. The triangular markings tend to be more visible to oncoming traffic than the broken lines currently used in the United States.

The FHWA and MUTCD give little guidance for striping in regards to lane use other than to suggest that where specific lane use signs are present on approaches with more than one lane, it is recommended that corresponding arrows be painted on the pavement.

According to the FHWA, pavement markings should be provided around raised splitter islands and right-turn bypass islands in order to increase driver recognition of the changing roadway. These markings should be yellow to the left of the traffic stream and white to the right of the traffic stream. In the case of a splitter island, pavement markings should be yellow adjacent to the entry and exit, and white adjacent to the circulatory roadway.

It is the recommendation of the FHWA that lane lines should not be striped within the circulatory roadway, regardless of the width of the circulatory roadway because it is believed that these lane lines give drivers a false sense of security. In addition, bike lane markings are not recommended because the additional width provided by the bike lane causes drives to increase speeds and therefore, leads to increases in vehicle-bicycle collisions. Instead, it is recommended that bicycles circulate the roundabout with the flow of traffic or by the use of shared bicycle-pedestrian crossings.

There are mixed views on whether pavement markings should be included in the circulatory roadway and what type of markings should be included if any. As shown above, the FHWA does not recommend the use of any pavement markings in the circulatory roadway because drivers in the United States are not experienced enough in the rules of navigating roundabouts. Lane lines in the circulatory roadway have a tendency to confuse drivers on which lane to use and whether they can exit the roundabout from their current lane. In addition, lane lines circulating the entire roundabout can trap vehicles in the inside lane.

Although the FHWA does not recommend the use of lane markings, such markings are in use in Europe and Australia and have been proven effective where users understand the rules for navigating the roundabout. The types of marking used in Europe and Australia were covered in *Signing and Pavement-Marking Strategies for Multi-Lane Roundabouts: An Informal Investigation* by Kinzel.(7) According to Kinzel, there are two views currently in practice regarding markings at roundabouts. The first is the “laissez fair” approach, which provides no markings at all within the roundabout. In this case, lane changes inside the roundabout are not discouraged, so lane markings are not provided in the circulatory roadway. Instead, drivers jockey for position within the roadway. This approach can leave drivers, especially inexperienced drivers, uncomfortable entering the roundabout side-by-side with another vehicle and unsure how to navigate the roundabout.

The second approach Kinzel discusses in the “positive guidance” approach, which uses circulatory striping and advance lane-use control signs to reinforce lane use within the circulatory roadway. In this case, circulatory striping often attempts to match circulating lane choice with the exit lane choice. In this case, drivers may be more comfortable entering the roundabout side-by-side with another vehicle because lane positioning is made more explicit.

While the FHWA guide tends to recommend the “laissez faire” method, the MUTCD is less clear on how striping should be used in roundabouts. Section 3B.24 of the MUTCD gives a single sentence regarding circulatory striping in multi-lane roundabouts, which says “Lane lines may be used on the circular roadway if there is more than one lane.” The use of the word “may” suggests that striping is neither encouraged nor discouraged, but instead left to the discretion of the designer. However, sections 3B.04 and 3B.08 of the MUTCD define four types of marking patterns and indicate where they should be applied:

- A double line indicates maximum or special restrictions, and shall be used where crossing the lane markings is prohibited.

- A solid line prohibits or discourages crossing, and shall be used where crossing the lane line markings is discouraged. A solid lane line can also be used to extend a lane line through an intersection, indicating greater restriction than a dotted line.

- A broken line indicates a permissive condition, and shall be used where crossing the lane line markings with care is permitted

- A dotted line provides guidance, and should be used, when desirable, to extend a lane line through an intersection.

Kinzel covers several patterns of lane striping at roundabouts that comply with these rules set forth in the MUTCD. These patterns are combinations of three types of striping: striping extending the inbound lanes into the roundabout (denoted I), circulating striping (denoted C), and striping extending outbound from the circulating lanes to the exit lanes (denoted O). In addition to these combinations, Kinzel identifies a situation in which no striping is included in the circulating roadway.

The first striping pattern that Kinzel discusses is the IO pattern, which provides extensions of the inbound and outbound lanes, but contains no circulating striping. This striping pattern provides some lane use enforcement by encouraging entering and exiting vehicles to maintain lane choice. However, it gives no guidance for lane usage in the circulating roadway and does not discourage lane changes. For some striping patterns, Kinzel discusses both solid and dotted patterns. However, dotted lines are the only IO pattern that is considered compliant with MUTCD regulations.

Kinzel also discusses the C pattern, which is typically known as “partial” or “partial concentric” striping. This pattern discourages lane changes within the roundabout, especially when solid lines are used. While lane use guidance is not explicitly given to entering and exiting vehicles, entering vehicles are likely to be guided into the correct lane by seeing the circulating striping ahead. Figure 2 below shows the solid pattern for partial concentric striping.

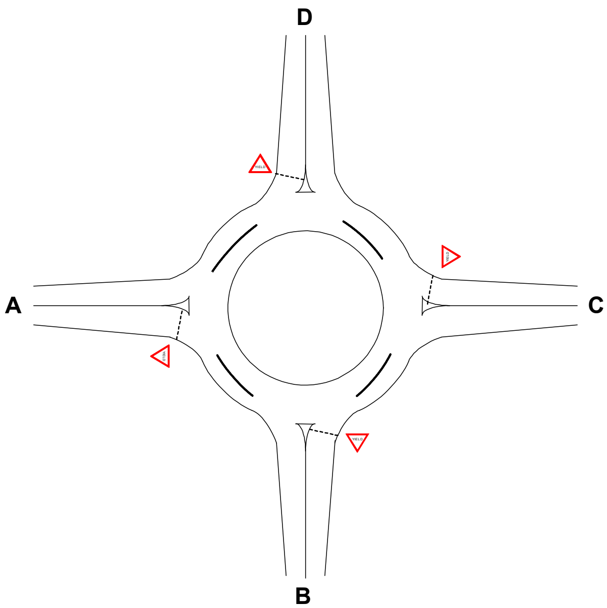


Figure 2 "C" or "partial concentric" striping

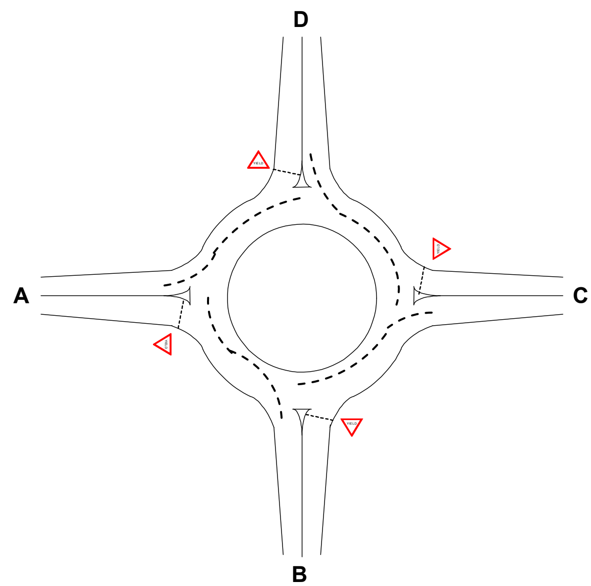


Figure 3 "CO" or "concentric-spiral" striping

Kinzel also discusses the CO pattern, which is also called the "Alberta" or "concentric-spiral" striping pattern. This pattern is considered more efficient than the "C" pattern because it gives guidance at what is considered the most confusing section of the roundabout, the exit. There are three different variations of the CO pattern that are MUTCD compliant:

- co – contains dotted lines for the C and O portions of the striping
- Co – contains solids lines for the C portion and dotted lines for the O portion of striping
- CO' – uses all solid striping with gaps in front of the entering lanes

An example of the co pattern is shown in Figure 3 above.

Kinzel also discusses the ICO pattern, which is similar to the co pattern shown in Figure 3 above, except that it adds entry extensions into the circulating roadway. Some confusion may occur regarding the intersection of the extension lines for the entering and exiting traffic flows. However, this type of pattern is similar to the pattern drivers experience at a signalized intersection when left-turn lane line extensions from adjacent approaches cross each other.

The final striping pattern discusses by Kinzel is commonly known as "concentric" striping and is referred to as C_∞ by Kinzel. This pattern includes a continuous lane line around the entire circulatory roadway. This type of striping pattern is criticized by the FHWA as potentially trapping circulating vehicles in the inside lane. In addition, it does not provide guidance at the exit and can drivers to be believe exiting from the inside lane is prohibited. It also gives the impression that it is acceptable to continue circulating in the outside lane.

While FHWA recommends that no striping be placed in the circulating roadway and the MUTCD gives little guidance for circulating roadway striping, Kinzel recommends the use of the Co pattern for striping in the circulatory roadway. This pattern complies with MUTCD rules for striping. It includes solid lines for the circulating roadway and dotted lines for the exiting lane extensions. According to MUTCD guidelines, this pattern discourages lane within the roundabout and gives guidance to drivers at the exits.

Safety Analysis for NJDOT Project 2002-16 Sites

The Department for Transport published a document called the *Road Safety Good Practice Guide*, which provides engineers with an outline for how to perform a safety analysis on an intersection or a roadway.[26] This document discusses how to identify and prioritize safety issues, as well as how to design safety measures to correct these issues. One chapter of this document is dedicated to discussing specific safety problems that currently exist nationwide and several engineering measures suggested as solutions. It should be noted that this document is written in reference to intersections and roadways, not specifically roundabouts or traffic circles. It should also be noted that this document refers to facilities in Great Britain. Current practice in the United States may vary. However, since this approach was introduced in Great Britain, road deaths have fallen by 39 percent and serious injuries by 45 percent. This occurred while the volume of traffic increased by 160 percent.

As the *Road Safety Good Practice Guide* points out, accident analysis is a difficult process, especially when it comes to identifying the source of an accident problem.(26) The reason for this is that there are numerous factors affecting accident occurrences and these factors are not independent. Therefore, a comprehensive analysis of the accident data must be performed. This document provides a guide for performing this analysis to ensure that the key areas and types of accidents are addressed.

The following section outlines the steps that were taken while performing the safety analysis on the traffic circles in NJDOT Project 2002-16. These steps are based on common practice in Great Britain as outlined in the *Road Safety Good Practice Guide* and common practice in the United States.(26)

Step One – Site Visit

The first step involved in performing a proper safety analysis is to familiarize oneself with the site. This should include a visit to the site to observe traffic flows, pedestrian activity, bicycle activity, lighting, sight distances, roadway layout and geometry, signage, and any other factors that could contribute to collisions. While visiting the site, it is important to note any locations where glass or remnants from a collision may be left at the site. This may indicate a location where frequent collisions occur, especially accidents causing property damage.

The visitor should also look for damage to guide rails, curbs, signs, trees, etc. that may have been caused by a collision. Pictures should be taken of all of these observations. In addition, videotaping traffic patterns may be an effective method for recognizing potential safety risks.

Rutgers University and Rensselaer Polytechnic Institute students have performed this step in the process for NJDOT Project 2002-16 through extensive data collection. Several site visits were completed to each of the traffic circles of interest. The first was for the project team to become familiar with the facilities. Additional site visits were conducted to gather pertinent information including traffic counts for peak hours, general traffic patterns, and field measurements as well as to record video footage of the facilities for an entire day. The video footage was recorded by approach as well as with an omni-directional camera mounted on a mast to record movements from a "birds-eye view."

Step Two – Obtain Collision History

To conduct a proper safety analysis it is necessary to obtain the collision history for the site from the state department of transportation. The *Road Safety Good Practice Guide* recommends obtaining accident reports for a period of three to five years.(26) Typical accident analyses in the United States are based on at least three years worth of accident data.

Accident reports for the three sites were obtained from NJDOT. A detailed accident report was also provided in the Delaware Valley Regional Planning Commission report.(32)

Step Three – Create Collision Diagrams

From the information contained in the accident reports, collision diagrams were created for each of the traffic circles. These diagrams include a stick-figure type of drawing of each of the collisions during the study period. Supporting information for these diagrams include the cause of the collision, the severity of the collision including number of injuries or amount of property damage, roadway and weather conditions. These collision diagrams can be seen in the accident history section for each site.

The *Road Safety Good Practice Guide* recommends that these collision diagrams be created with a GIS system or an accident analysis package that will plot the collision on a map.(26) These maps should initially distinguish killed and seriously injured (KSI), child accidents and/or other vulnerable groups separately.

These collisions diagrams are similar to typical collision diagrams created for intersections, however, there are some aspects unique to collision diagrams for the traffic circles. For example, symbols are not included on collision diagrams for typical intersections for such accidents as running over the splitter island or running over the center island. Symbols for these types of collisions were creating for the diagrams.

These collision diagrams should also indicate where a rule of navigating the circle has been broken. For example, if a vehicle exits the traffic circle from the left hand land and collides with a vehicle attempting to continue around the circle in the right hand lane, has a rule of operation been broken? If so, who was responsible for breaking this rule? If a general rule was broken, was there some contributing factor, which led the driver to believe that this rule was not in existence in this location or that some other rule applied. For example, does the striping on the roadway indicate that the left-hand driver should have continued around the circle or that the right-hand vehicle should have exited?

Step Four – Prepare Data Table

This step performed simultaneously to creating collision diagrams. This step involves organizing the data contained in the accident reports into a spreadsheet or tabulated form. The spreadsheet should include the location of the collision, the type of accident, number and severity of injuries, amount of property damage, and causes for the collision. In addition to these factors related to the collisions, the database should include information such as vehicle flow at the accident site, pedestrian and bicycle flow at the accident site, geometry of the site including roadway width, radius of curvature, length of roadway segment, etc. The purpose of this database is to examine accident patterns in terms of type, contributory factors and location, considering accident numbers and rates for each class of road. The analysis of the types of accident and the causal factors contributing to the accident is a vital step to reach an understanding of why accidents occur and how to treat the problem. Some of the most important aspects to be studied include casualty, severity, weather and road surface condition, road layout and junction type, vehicle maneuvers, vehicle types, vehicle speeds, driver compliance with the Highway Code, driver age, pedestrian involvement etc.

The *Road Safety Good Practice Guide* suggests tabulating the results of the analysis in order to assess the relative importance of each of the safety problems and prioritize them.(26) This could prove useful in identifying any overall problems such as speeding or skidding. When ranking the problems, the assessment should be based on accident rates, number of accidents, and severity of injuries sustained in accidents. In Great Britain, an intervention level is a measure of an accident problem using a numerical value. It is typically represented in terms of accidents per year at an intersection or accidents per vehicle-kilometer on a stretch of roadway. If the values for a particular intersection or roadway segment exceed a certain intervention level, that facility is typically selected for evaluation and improvement. In the United States, a similar factor is used, called the critical rate factor or CRF. A value of less than 1.0 indicates that the facility experiences fewer collisions per year than other similar facilities. A value of greater than 1.0 indicates that the facility experiences more collisions per year than similar facilities. Therefore, an accident problem is said to exist where the CRF is greater than 1.0.

As the *Road Safety Good Practice Guide* states, accidents are highly correlated with traffic flows and road lengths.[26] Therefore, you would generally expect to find more accidents on a long road with high flows than on a short road with low flows. Because of this idea, it is important to take into account exposure, or the opportunity for accidents to occur, when ranking accident problems. The guide also points out that while the goal is ultimately to reduce the number of accidents and injuries within the budget, the way to do this may not necessarily be to treat the locations with the most accidents. This is because sites with a high accident risk are the sites that are most likely to be amenable to treatments. In other words, the sites that do not have the largest number of accidents, but do show a greater risk for accidents than we would expect to see at that site, are the sites that would be most greatly impacted by safety treatments. The guide also notes that while the most important exposure variables are likely to be road length and vehicle flow, other factors such as pedestrian and bicycle flow should also be examined.

Step Five – Identify Accident Patterns

Based on the collision diagrams and the spreadsheets created for each traffic circle, the next step involves identify accident patterns. Patterns may be identified based on accident location or type of collision. An example of an accident may be an overwhelming number of rear-end collisions at one of the approaches to the traffic circles. This accident pattern would suggest that there is a design flaw at this approach that could be corrected through safety treatments. Another example of an accident pattern is a large number of single-vehicle accidents in one location along the circle. This may indicate that speeds are too high in this location or that the radius of curvature is inadequate for making the maneuver. These patterns for the three circles of interest can be seen in the site-specific sections within this report.

Step Six – Identify Contributing Factors

Once accident patterns have been clearly identified, the study team began identifying the leading contributing factors in causing the collisions. A list was made of possible causes for these collisions. Additional site visits were made to further identify causes of such collision patterns and determine whether speculated causes are possible.

The *Road Safety Good Practice Guide* provides a list of questions that an engineer should ask while performing a site visit in order to identify safety issues.(26) Some of these questions are as follows:

- Is there a consistency and clarity of approach in the quantity, quality, type and standard of maintenance of layout, signs and markings along the road?
- Is correct warning of a hazard given on the approach by use of the proper road markings hazard centre line, SLOW marking and so on as set out in the TSM (Note that the TSM in Great Britain is similar to the Manual on Uniform Traffic Control Devices or MUTCD in the United States).(31)
- Are the markings properly maintained, so that they are clearly visible by day and by night and give the necessary minimum preview time?
- Are the prescribed warning signs provided according to the TSM (MUTCD in the U.S.)?
- Are the signs the correct distance from the hazard?
- Are the signs the correct size for the prevailing traffic speeds?
- Are the signs properly maintained and in good condition?

- Can the signs be clearly seen over the full recommended visibility distance or are they obscured by foliage, other signs, parked vehicles etc?

- Are the signs sited under trees or otherwise in deep shadow for much of the day

- Are signs difficult to see because they are viewed against a complex background?

- Are signs difficult to pick out at night because they compete for attention with brightly lit advertisements, shop fronts, etc.?

- Have the needs of all road users and vehicle types been taken into account, as far as is practically possible?

Step Seven – Identify Other Considerations

The *Road Safety Good Practice Guide* points out that other factors may contribute to collision other than those that are readily apparent in the design of the facility.(26) Such factors may be related to changes in roadway conditions or design features. In addition, a new development in the vicinity of the facility may have lead to changes in traffic volumes or traffic patterns at the facility. It further notes, that the following questions should be asked and answered when conducting a safety analysis at any facility:

- Have accident frequencies changed nationally?
- Have traffic levels changed?
- Has the composition of traffic changed?
- What other local or national events may have affected accident frequencies?

An example of an underlying contributing factor to collisions is that in Maryland, the number of roundabouts is rapidly growing. However, there is a learning curve involved with such a change in design procedures. Therefore, there may be a large number of collisions soon after the roundabouts are installed while drivers adjust to the change. These collisions may taper off as drivers become accustomed to driving through these facilities.

An underlying contributing factor that may be relevant to the traffic circles in NJDOT Project 2002-16 is the prosperity of the establishments located around the circle. Particularly at the Asbury Park Circle, there are a number of curb cuts along the circle that provide access to a number of businesses. When business is good at a given business, more traffic will be entering and exiting that business' driveways, creating less safe traffic conditions. Therefore, we may see a buildup of collisions near driveways where a business is performing particularly well.

Step Eight – Identify Possible Safety Treatments

After identifying the major factors that contribute to collisions, possible measures to correct these safety issues were identified. These lists were fairly comprehensive, including list of all possibilities that were narrowed down later.

Once the list of possible solutions was made, the list should was prioritized in terms of costs and how effective each treatment is anticipated to be. Those treatments that would prove far too costly for the benefit they would provide, was eliminated from the list.

The next step included identifying those treatments that can actually be observed or modeled in the PARAMICS software package and separate them from those that cannot. Treatments that are more easily modeled in PARAMICS include, but are not limited to:

- Speed control
- Lane Control/Lane utilization

- Signage
- Entry curvature/geometry
- Roadway width
- Right of way/priority

It is important to note that signage has been included in the list of treatments that can be modeled in PARAMICS, however, not all signage treatments are capable of being modeled. We can indicate the location of certain signs such as speed limits or advance warning signs. We can also indicate the driver behavior that they are intended to create. However, we cannot model signage in terms of: size, color, reflectivity, height, phrasing, design, etc.

Although some treatments may not be able to be modeled in PARAMICS, this should not exclude them from the list of recommended treatments for the facility as some of them may prove more effective than those treatments that can be modeled. Therefore, all safety treatments are included in the final report.

Conclusions & Recommendations

A number of references currently exist that give guidance for performing a safety analysis at roundabouts. Some examples of these documents are the British *Road Safety Good Practice Guide* and the Australian *Guide to Traffic Engineering Practice*.(26,3) However, as traffic circles are used primarily only in the United States and are often being replaced with roundabouts, few documents exist to provide guidance for performing a safety analysis on these facilities. Therefore, the methods used in guides for intersections and roundabouts have been adapted to provide a basis for performing the safety analysis of the traffic circles in NJDOT Project 2002-16.

Based on this guidance, we determined a series of eight steps that were executed to complete the safety analysis. Those steps are as follows:

1. Site Visit
2. Obtain Collision History
3. Create Collisions Diagrams
4. Prepare Data Table
5. Identify Accident Patterns
6. Identify Contributing Factors
7. Identify Other Considerations
8. Identify Possible Safety Treatments

Safety Methodology

This section describes the safety analysis methodology used for the three traffic circles studied: 1) Collingwood, 2) Brooklawn, and 3) Asbury Park.

Introduction

Now discussed is the safety analysis methodology completed by Rensselaer Polytechnic Institute (RPI) in conjunction with Rutgers University (Rutgers) for the NJDOT Project 2002-16. This chapter provides the reader with an overview of the safety analysis process developed to assess crash safety under current and potential alternative future conditions at the traffic circles under study. The methodology created below was used for each of the three New Jersey traffic circles under study: 1) Collingwood, 2) Brooklawn, and 3) Asbury Park.

Methodology

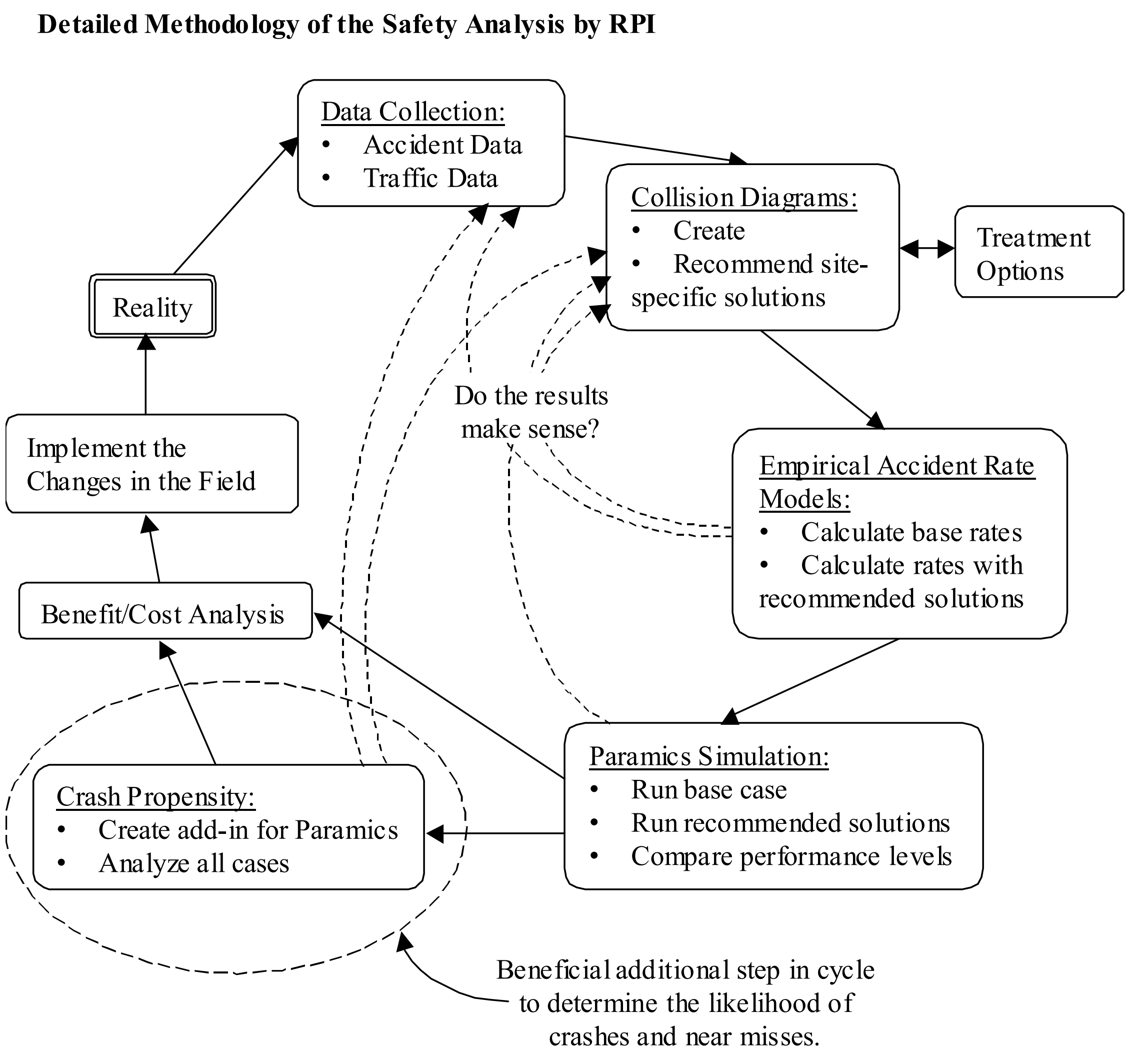


Figure 4. Analysis process

In Figure 4, we present an overview of the methodology being implemented. The first steps for each site are collecting information about and studying the existing conditions, then developing potential treatments to be tested and compared to the current conditions and each other. The second set of steps includes assessing each scenario in two manners, via select empirical models and via

PARAMICS simulation. Next are results comparisons, qualitatively and quantitatively, plus a benefit/cost analysis. Finally, the best treatment option for the conditions at hand is chosen and implemented. This cycle includes a series of feedback loops (designated by the dashed arrows in Figure 4) for learning and assessment of treatments. The cycle also includes the potential for repetition to further improve the traffic circles in an iterative and incremental process. Now, the major steps are discussed in further detail.

Existing Conditions

DATA COLLECTION

Observing a facility is one of the most important steps to reaching a clear understanding of how the geometrics, signage, and markings control and affect operations as well as driver behavior. Therefore to conduct safety assessments at the study traffic circles, both accident data and traffic data was collected. The accident data were used to:

- Pinpoint crash locations within and near the traffic circles,
- Determine which crash locations are most frequented, and
- Recommend treatments based on the specifics of the facility design and crashes (type, time of day, pavement conditions, and so on).

Additionally, traffic data were employed to:

- Characterize speed-flow-density relationships,
- Determine which crash locations potentially impact circle operations heavily due to high speeds, flows, or densities at said locations, and
- Analyze existing conditions and proposed treatments with the aid of a simulation program, PARAMICS.

CRASH ANALYSIS, TREATMENT SELECTION

Crash diagrams were created at each of the three traffic circles of interest based on police reports between 2000 and 2002. These diagrams provided insight for each accident, such as the location, type of accident, time of day, weather conditions and severity. After analyzing the accident patterns at each of the sites, a set of proposed treatments was developed. In some cases, such as Brooklawn, there have been previous studies that also present possible safety treatments. A comprehensive list of possible treatments was compiled for each of the sites.

TRAFFIC VOLUMES

In addition to an examination of the crash histories, peak period traffic volumes were collected on a weekday at each site, as shown in Table 4. The process of data collection was described in the Safety Treatments chapter.

Table 4. Traffic Data Collection

Traffic circle site	Date & times of data collection
Asbury Park	Friday, 10/31/2004 7-9 a.m. & 3:30-5:30 p.m.
Brooklawn	Wednesday, 4/21/2004 7-9 a.m. & 3:30-5:30 p.m.
Collingwood	Thursday,10/30/2003 7-9 a.m. & 3:30-5:30 p.m.

AVERAGE ANNUAL DAILY TRAFFIC (AADT)

Although simulation models can be adequately run using only hourly data, daily traffic data in and around the traffic circles were needed for the empirical models. Therefore, the AADTs required determination. Both Asbury Park and Collingwood AADTs were estimated based on two data sources: the peak period data our research team collected and available NJDOT AADTs from the straight line diagrams (located at: www.state.nj.us/transportation/refdata). Brooklawn

AADTs were drawn from the Delaware Valley Regional Planning Commission (DVRPC) report.[32]

Modeling Process

ANALYTICAL MODELS

The research team sought out empirical and analytical models in the transportation literature that could relate traffic circle geometry, operations, and traffic conditions to the safety of a facility. The primary models of interest were safety models designed for assessing roundabouts. The most detailed are the level 3 models that examine each approach of a roundabout individually. These models provide ample insight for our analysis. Two of the single vehicle accident models that were identified include:

1.) Maycock & Hall - UK Model (1984)

2.) Arndt's Model – Australian Model (1998)

Other models for roundabouts, signalized and unsignalized intersections were included to ensure accurate depictions of each of the sites for the major accident types. The research team then examined a host of potential models for applicability to the study objectives, recommending a few (please refer to the Review of Safety Models chapter). In brief, it was necessary to choose models that were developed for roundabouts due to the fact that little or no safety models exist for traffic circles.

As noted in Figure 4, following the collision diagram work the team analyzed the validity of the recommended empirical models with respect to the base conditions at each traffic circle. When the models were validated, and calibrated to the facilities under study (as necessary), then the proposed treatments were analyzed. The realized solutions should indicate whether or not the facilities are more or less safe with the treatments in place. At this point, feedback loops are within the analysis process (shown in Figure 4) to ensure the results are compared to both the collision diagrams and the accident data for reasonableness.

In general, while RPI is validating and running the empirical and analytical model calculations, Rutgers simulated the scenarios at each facility, then passed the output data to RPI for analysis. Further specifics of the PARAMICS simulations now follow.

PARAMICS SIMULATION

Once possible treatments for the sites were identified and agreed upon the simulation modeling began. The team defined PARAMICS treatments and necessary treatment proxies (see Table 6). These were derived from the comprehensive list of treatments at the site. After this step was completed, the team modified the PARAMICS model to reflect each of the proposed scenarios. Since the PARAMICS software does not respond to all geometric changes, nor does it respond to some marking or signage changes, it was used primarily as a verification tool to prove a change can be implemented.

When using a simulation program such as PARAMICS, each scenario must be run numerous times so that different starting conditions can be included for a balanced assessment of a scenario. In simulation terminology, this change in starting conditions is guided by one or more “random number seeds”. In many software programs, the seed values may be explicitly chosen by the user for each run, or they can be automatically calculated using a “random number generator”. When multiple seed values are needed to start a simulation run, multiple random number “streams” are created to ensure each value for a particular run is independent of the other seed values for that run. The PARAMICS environment (since version 4) includes several predefined random number streams, each matched with a separate function or variable, such as lane changing behavior, car following, and so forth. [(33)] All of these streams start from one seed value each run to simplify beginning the simulation. The benefit of a single starting seed is one can easily change all the streams from run to run, the drawback of this method is one does not have the ability to fix certain streams while varying other streams which is a helpful variance reduction technique.

To assess each scenario and compare them to one another, multiple runs of each scenario are made (each with a different seed as discussed above). A confidence level for all statistics is predefined to ensure comparisons are relevant. Therefore, the number of runs necessary may vary from statistic to statistic (like from mean speed to the standard deviation of the gaps) to reach the desired level of confidence. Generally, it has been found during this research that ten or fewer runs of each scenario are necessary to achieve the appropriate confidence level.[(34)]

Once all the base case modeling steps were complete the results of each of the methods were compared to each other and, again with feedback loops, to the collision diagrams and accident data. The results of each of the modeling techniques were quite different with one supporting the other. For example, the empirical models yield annual accident rates based on traffic volumes and facility geometry while the simulation output yields performance measures focused on generated speeds, traffic flows, and similar characteristics. Therefore, patterns were expected to arise between the two modeling processes such as if speeds are lower, then fewer accidents are expected. Once these patterns were recognized, the team could then develop the crash propensity tool; however, this is not part of the current project’s work scope but is briefly discussed for informational purposes.

Crash Propensity Modeling

Although not within the scope of the current project, the authors think it is vital to inform the reader of a tool that could be created to extend and strengthen the current solution process by not only looking at accident histories to predict safety but by calculating the likelihood of crashes and near misses, thereby capturing a missing performance measure (likelihood) and a missing element (near misses). An add-in, or piece of code, can be created for the PARAMICS simulation program to collect statistics on crash propensity. As can be seen in Figure 4, the crash propensity modeling and analysis could be cleanly added to the current safety analysis methodology.

Cost Benefit Analysis

Once all of the treatment options' safety models were completed, a cost-benefit (B/C) analysis was conducted. Following the results of B/C analysis, the team was able to present the results and recommendations for each of the three traffic circles.

Treatment Implementation

Following the project team's recommendations, the NJDOT can make the ultimate decisions of which treatments to implement at each site and proceed.

New Cycle Iteration Begins

It is recommended that approximately 6 months after each treatment implementation data be collected, consistent with original collection methods and locations, to enable the conducting of a formal before and after study. Such a study can close the safety analysis loop by providing much needed field data that can empirically substantiate the findings of this project. Moreover, results of the study can point to new treatments that may be desirable at one or more of the facilities. Finally, with this analysis process in hand and tested, the NJDOT can apply it to traffic circles throughout the state.

Project Analysis Background

In the Techniques for Evaluating Safety chapter, several predictive accident models were discussed that could be used to evaluate the reduction in collisions created by applying various safety treatments. Table 1 gives a list of the independent variables included in those predictive models. These independent variables have been shown to have a significant impact on safety at roundabouts and were used for developing effective safety treatments.

In the Safety Treatments chapter, several safety treatments were described that have the potential to reduce collisions or the risk of collisions at the traffic circles included in this project. Table 5 connects the safety treatments to the predictive accident models from the Techniques for Evaluating Safety chapter.

Eight PARAMICS input parameters seem to have value in describing the effects of safety treatments:

- Speed, either as speed limits or percentage reductions in speed
- Gap acceptance probability distributions
- Safe distance – for following headways
- Visibility – as in the first point on a side road where vehicles on the main road can be observed
- Lane usage – to control vehicle trajectories through the traffic circle
- Driver type/driver behavior – to reflect variations in car following and lane-changing behavior
- Sight distance – to capture variations in the visibility of vehicles upstream of an entry point
- Signage – to alert drivers to upcoming events, geometric features, etc.

Table 5. Accident prediction models and their parameters

Parameter Name	Models: **Maycock & Hall (UK - 1984)**	Entering-Circulating	Approaching	Single Vehicle	Pedestrian	**Arndt (Australia - 1998)**	Single Vehicle	Approaching Rear-End	Entering/Circulating	Exiting/Circulating	Sideswipe
Operational Parameters											
Entering Flow (AADT)		X	X	X	X			X	X		
Circulating Flow (AADT)		X						X	X	X	
Exiting Flow (AADT)					X					X	
Pedestrian Flow					X						
AADT (in direction considered)							X				X
Entering Speed (85th Percentile)							X	X	X		
Circulating Speed (85th Percentile)							X		X	X	
Exiting Speed (85th Percentile)										X	
Point-to-point Travel Time									X		
Percentage of Motorcycles		X									
Radius of Vehicle Path							X				
Length of Vehicle Path							X				
Geometric Parameters											
Entry Path Curvature		X	X	X							
Entry Width		X	X								
Approach Width		X		X							
Inscribed Circle Diameter		X									
Central Island Diameter		X									
Angle Between Arms		X									
Gradient		X	X								
Sight Distance			X	X							
Approach Curvature				X							
Number of Lanes								X	X		
Point-to-Point Distance									X		
Potential Side Friction											X

Table 6. Safety treatments and their corresponding model parameters

Model Parameters	Safety Treatments: Speed	Angle Between Entering Roads	Entry Deflection	Entry Width	Approach Width	Approach Curvature	Entry Curvature	Sight Distance	Signage	Striping	Central Island Diameter
Operational Parameters											
Entering Flow (AADT)											
Circulating Flow (AADT)											
Exiting Flow (AADT)											
Pedestrian Flow											
AADT (in direction considered)											
Entering Speed (85th Percentile)	D	I	I	I	I	I	I	I	D	I	I
Circulating Speed (85th Percentile)	D	I	I				I	I	D	I	I
Exiting Speed (85th Percentile)	D							I	D	I	I
Point-to-Point Travel Time	I	I	I	I	I	I	I	I	I	I	I
Percentage of Motorcycles											
Radius of Vehicle Path		I	D			D	D			I	I
Length of Vehicle Path		I	D			D	D			I	I
Geometric Parameters											
Entry Path Curvature		I	D	D			D			I	
Entry Width				D						I	
Approach width					D					I	
Inscribed Circle Diameter										I	D
Central Island Diameter										I	D
Angle Between Arms		D									
Gradient											
Sight Distance		I		I	I		I				I
Approach Curvature		I					D			I	
Number of Lanes										D	I
Point-to-Point Distance		I	I				I			I	I
Potential Side Friction											

D = The safety treatment at the right is intended to impact the model parameter at the left
I = The safety treatment at the right may indirectly influence the model parameter at the left

Supplementing the simulation-based analyses, empirical and analytical models were employed to verify the PARAMICS results. Based on the review presented in the Review of Safety Models chapter several models including Maycock and Hall (1984), Arndt (1998) and Brude and Larsson (1997) were used to evaluate each of the traffic circles of interest. Since each of the models was developed to analyze specific events for different facilities the results will not be comparable.

The team defined PARAMICS treatments and treatment proxies. These treatments were derived from the comprehensive list of treatments at the site. The treatments were then grouped into scenarios and the team modified the PARAMICS models to reflect each scenario. Based on the simulation runs, conclusions were drawn about the efficacy of the various treatment options. Those that seem most promising are described in this report.

To ensure statistical significance, since the simulations involve randomness, several simulation runs were made for each scenario until a pre-determined confidence level was achieved. Each simulation run was assumed to be independent of the others provided that different random number seeds were employed. To further ensure independence, the study team used the feature in PARAMICS, which activates different random number streams for different aspects of the simulation. (When this feature is selected, PARAMICS takes the number seed specified by the user and activates separate random number streams for different aspects of the simulation like vehicle releases, lane changes, and car following. Hence, even though the user provides only one seed input – plus the flag that multiple seeds are to be employed – PARAMICS activates multiple random number streams based on the fact that the flag has been set.)

The remainder of this chapter focuses on the Collingwood, Brooklawn and Asbury Park traffic circles. The existing accident patterns are presented as well as empirical and analytical analysis for selected alternatives.

Collingwood Circle Analysis

In this section, the Collingwood circle is analyzed. The Safety Methodology chapter provides an overview of the process that included the simulation analyses, the empirical analyses, comparison of these results and a benefit/cost analysis. At the end of this section there are recommendations for the Collingwood Circle based on the quantitative and qualitative assessments.

Study Location

Collingwood Circle is a large traffic circle located in Collingwood, New Jersey. This facility is notable for its rather high speeds and unusual geometry.

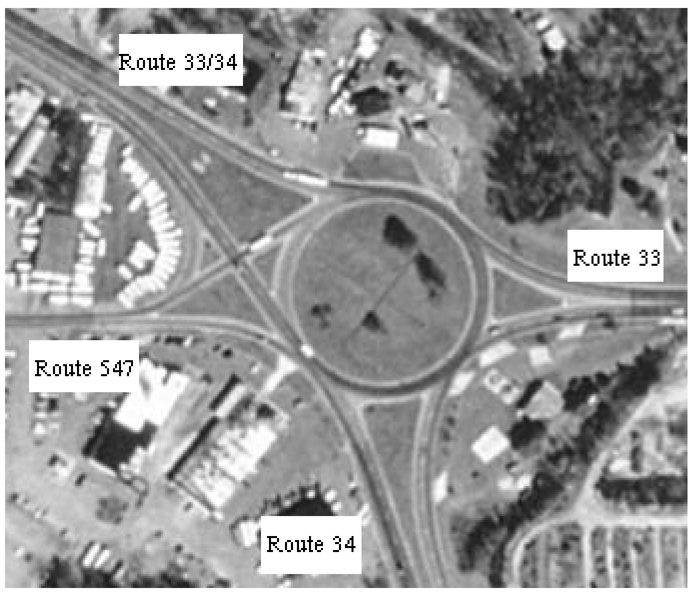


Figure 5. Collingwood circle

As shown in Figure 5, the Route 547 exit crosses the Route 33/34 entrance to the traffic circle in a stop-controlled intersection. As also shown in the figure, this is a rather large traffic circle with fairly tangent approaches. The presence of tangents allows vehicles to navigate the facility at high speeds of up to 50 mph, especially when traveling from Route 33/34 southbound to Route 34. Another key feature of this facility is that entering traffic has the right-of-way on nearly all approaches, while circulating traffic must yield. The only exception to this rule is on the Route 547 eastbound approach, where entering traffic yields to traffic already in the circle. Also, as shown in the diagram, this is a two-lane facility, although no striping exists within the circle itself. Where Route 34 southbound and Route 33/34 northbound exit the circle, the roadway is wide enough to accommodate three lanes of traffic. At times, vehicles use the roadway as two lanes and when congested, particularly when a queue extends from the next entry back to the diverge point, vehicles use the roadway as three lanes.

Accident History

Accident reports for 2000 through 2002 were obtained from the NJDOT for all accidents occurring inside the traffic circle and up to 1,000 feet upstream on each approach. A collision diagram was prepared to determine accident patterns in the facility; it can be seen in Figure 6. In addition, a database was created that contains the following information about each collision: location of collision, type of collision, number of injuries, number of fatalities, road surface conditions, light conditions, date of collision, apparent contributing factors, and secondary causes of collision. Based on the collision diagram and the accident database, a number of accident patterns were discovered and are discussed in the following paragraphs.

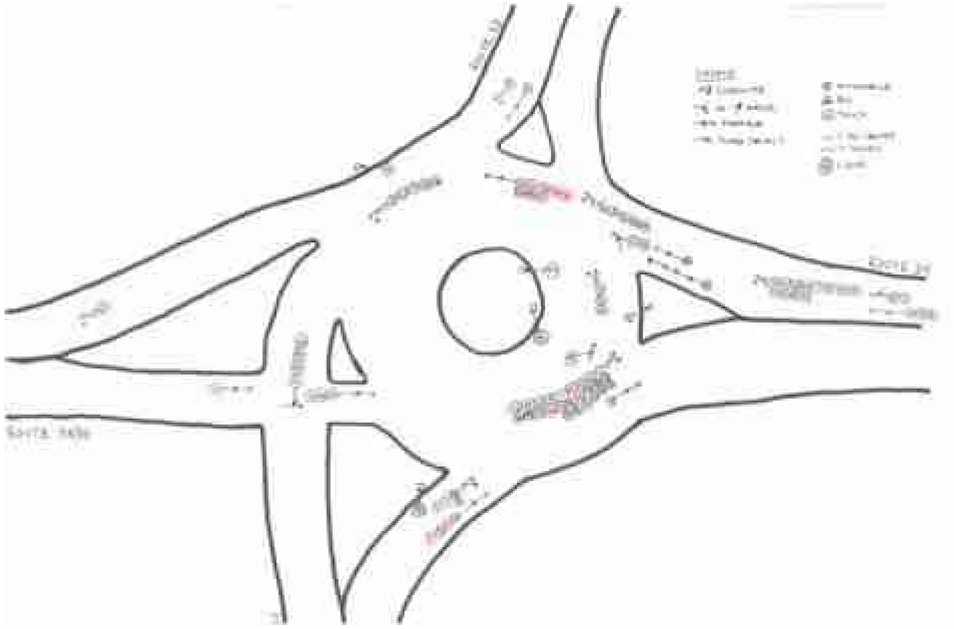


Figure 6. Collingwood collision diagram

Route 34 Northbound Approach

Approximately thirteen “same direction side-swipe” collisions occurred on Route 34 northbound approaching Collingwood Circle from 2000-2002. Of these collisions, one involved injuries, but was not serious. In addition, five “same direction rear-end” collisions occurred on Route 34 northbound approaching the circle during the study period. In addition, two “angle” collisions occurred on this approach, where a vehicle exiting a local business collided with a vehicle headed northbound on Route 34 toward the circle. The Traffic Engineering Handbook lists excessive speed and inadequate signing as possible causes of “same direction side-swipe” collisions.[35] That document also lists excessive speed, driver unaware of intersection, slippery surface, lack of adequate gaps, and crossing pedestrians as causes of “same direction rear-end” collisions at unsignalized intersections. On this approach, there is no merging traffic, therefore, gaps are not an issue. In addition, there are rarely pedestrians at

Collingwood circle, so crossing pedestrians may be neglected. As effective countermeasures for these accident problems, the Handbook lists reducing speed limit, installing illuminated street signs, and installing advance guide signs to reduce "same direction side-swipe" collisions. The Handbook recommends reducing speed limit, installing or improving warning signs, and providing "slippery when wet" signs as effective countermeasures for "same direction rear-end" collisions. Based on the predictive model for approaching collisions by Maycock and Hall (1984) , factors affecting the number of collisions on an approach are:(1)

- Entry flow
- Entry path curvature
- Sight distance
- Entry width
- Gradient category

Therefore, effective geometric design treatments would include designs that improve these characteristics. For approaching rear-end collisions, the main contributing factor is speed according to Arndt's (1998) Australian model.(10) Therefore, safety treatments designed to reduce speed should be applied.

Route 33 Eastbound / Route 34 Southbound

The most prominent accident pattern exists where Route 33 eastbound and Route 34 southbound diverge. Approximately 25 "same direction side-swipe" collisions, one angle collision and one "same direction rear-end" collision occurred at this point. Three of these accidents involved injuries. A major problem here is that drivers do not have adequate warning of the Route 34/Route 33 diverge and are not aware of the correct lane until immediately upon diverging. In addition, high speeds make it difficult for vehicles to maneuver to the correct lane within the allotted distance. Another problem is that lane changes are improperly performed due partially to lack of striping. Collingwood circle is wide enough for two lanes of traffic all the way around the circle, and in this area is wide enough for three lanes. However, no striping exists to suggest to drivers how they should navigate the facility. This leaves drivers confused as to whether they should navigate the circle in one, two, or three lanes. Countermeasures for reducing “same direction side-swipe” and “same direction rear-end” recommended by the Handbook are discussed in the paragraph above. In addition to the suggestions made above, the Handbook also recommends the following for reducing “same direction side-swipe” collisions: sign and mark unsafe passing areas, provide roadside delineators, improve grade and alignment, widen lanes, reduce speed limit, install centerlines, lane lines, and edge lines, install reflective markers, install/improve channelization, provide advance direction and warning signs. In addition, Arndt’s model lists the relative difference in speeds between exiting and circulating vehicles as a contributing factor to exiting/circulating collisions. As evidenced by the data collected in the field, and by the data contained in the accident records, this speed differential is a major contributing factor to collisions at this location.

Route 33/34 Southbound / Route 547 Westbound

Four “angle” collisions and one “same direction rear-end” collision occurred at this stop-controlled intersection between 2000 and 2002. Of these collisions, two involved injuries. Observation of the site shows that the sight distance exiting Route 547 westbound and excessive speeds on Route 33/34 southbound could be contributing to the occurrence of collisions at this location. Sight distance may be a major contributing factor to collisions at this location because drivers often have difficulty merging at high speeds and watching oncoming traffic.

Route 33/34 Southbound Approach

Three “same direction rear-end” collisions occurred on this approach between 2000 and 2002. One of these collisions involved injuries. The major contributing factor to collisions at this location appears to be speed and lack of advance warning that the drive is about to enter a traffic circle. In addition, some driver confusion exists over right-of-way. Countermeasures for approaching collisions were discussed above for Route 34 northbound approach and would apply at this approach as well.

Route 34 Northbound / Route 33 Westbound

Approximately eight “same-direction rear-end” and five “same direction side-swipe” collisions occurred at this location between 2000 and 2002. Of the rear-end collisions, four (about half) involved injuries. The major contributing factors appear to be speed and lack of adequate stopping sight distance. As vehicles enter the circle on Route 34 northbound, they have the right-of-way and are traveling rather quickly. Many drivers anticipate having right-of-way at the intersection with Route 33 westbound because clear sight distance exists across the circle and no advance warning of the yield has been given. In addition, volumes are often high on the Route 33 westbound approach, causing vehicles to stop on Route 34 northbound for an extended period of time, subjecting them to greater risk of a collision. The “same direction side-swipe” collisions occur when vehicles on Route 34 northbound wishing to continue north on Route 33/34 northbound collide with vehicles entering the circle from Route 33 westbound and either exiting to Route 33/34 northbound and Route 547 west, or continuing around the circle. This could be in part due to an inadequate weaving distance. This may also be partially due to a lack of striping at this location. Drivers become confused as to which lane they are should use to exit. This confusion may be increased by the closeness of the Route 33/34 north and the Route 547 west exits from the circle. Separation of these exits may reduce collisions at this location.

Route 547 Eastbound Approach

Four “same-direction rear-end” and four “same direction side-swipe” collisions occurred on this approach between 2000 and 2002. Of these collisions, two involved injuries. In addition, one collision occurred where a vehicle collided with the curb. Upon investigation, it was found that the driver of this vehicle was driving while intoxicated. Therefore, this collision was neglected when looking for accident patterns.

Route 34 Northbound / Route 33 Eastbound

Two “angle” collisions and eight “same direction side-swipe” collisions occurred at this location between 2000 and 2002. These collisions appear to be related to a large differential in speed between the entering traffic on Route 34 north and the circulating/exiting traffic on Route 33 eastbound. This accident pattern is worsened by driver confusion over which lane to use in navigating the facility.

Other

A total of three collisions with a fixed object, two “same direction side-swipe” collisions, and one “same direction rear-end” collision also occurred at Collingwood Circle during the years 2000-2002. However, the locations of these collisions are spread throughout the circle and do not indicate a particular accident pattern. Most of these collisions appear to be due to driver inattention.

Three-Year Crash Summary

Table 7. Summary of reported accidents: annual averages

	Number of Accidents		Severity			Accident Type				
Location	Total	Average per Year	PD[a]	PI[b]	F[c]	CM[d]	RE[e]	HO[f]	FO[g]	Other
Rte 34 NB Approach	20	6.67	6.3	0.3	0.0	5.0	1.7	0.0	0.0	0.0
Rte 33 EB/ Rte 34 SB Diverge	27	9.00	8.0	1.0	0.0	8.7	0.3	0.0	0.0	0.0
Rte 33/34 SB/ Rte 547 WB Intersection	5	1.67	1.0	0.7	0.0	1.3	0.3	0.0	0.0	0.0
Rte 33/34 SB Approach	3	1.00	0.7	0.3	0.0	0.0	1.0	0.0	0.0	0.0
Rte 34 NB / Rte 33 WB	13	4.33	3.0	1.3	0.0	1.7	2.7	0.0	0.0	0.0
Rte 547 EB Approach	8	2.67	2.0	0.7	0.0	0.0	1.3	0.0	0.0	0.0
Rte 34 NB/ Rte 33 EB	10	3.33	3.3	0.0	0.0	3.3	0.0	0.0	0.0	0.0
Other	6	2.00	2.0	0.0	0.0	0.7	0.3	0.0	1.0	0.0
Total	**92**	**30.67**	**26.3**	**4.3**	**0.0**	**20.7**	**7.7**	**0.0**	**1.0**	**0.0**

a Property Damage Only
b Personal Injury
c Fatality
d Cross Movement (or Angle)
e Rear End
f Head On
g Fixed Object

Selection of Safety Treatments

As a result of the of the accident history study, several safety treatments were developed as possibilities for Collingwood Circle. Those treatments are discussed in the following sections.

Entry Curvature and Deflection

Entry curvature is a main variable contributing to approaching collision frequency. Approaching collisions are a problem particularly on the Route 34 northbound approach where thirteen sideswipe, five rear-end, and two angle collisions occurred. A main contributing factor to these collisions is high speeds on this approach. Increasing the entry curvature and entry deflection on this approach will require vehicles to slow down as they enter the traffic circle.

Approaching collisions are also a problem, although minor, on the Route 33/34 southbound approach to the traffic circle where four rear-end collisions occurred. Vehicles on this approach are traveling very quickly at speeds of up to 50 mph due to the tangential entry path of this approach. In addition, the current geometric layout of the facility allows vehicles entering the facility from Route 33/34 and continuing south on Route 34 to enter the traffic circle and high speeds and travel straight through the facility without slowing down or curving. Increasing the entry curvature and entry deflection on the Route 33/34 southbound approach requires vehicles to slow down entering and circulating the facility. In addition, it requires that drivers recognize that they have actually entered a traffic circle and forces them to be more compliant to the rules of the traffic circle.

Approaching collisions are also a problem on the Route 547 approach where four sideswipe, four rear-end, and one fixed-object collision occurred. Increasing the entry path curvature might help reduce these collisions. However, several businesses and residences exist close to the roadway on this approach. Therefore, there is not adequate right-of-way to apply this treatment.

Roadway Width

One area where accidents occur quite frequently is at the diverge point for Route 34 southbound and Route 33 eastbound. Approximately twenty-five sideswipe collisions occurred at this location. One of the main contributing factors to these collisions is that vehicles often queue from the yield point on Route 33 eastbound back beyond the diverge for Route 34 southbound. Vehicles wishing to go southbound on Route 34 expect to be able to use either lane to do so and are often traveling at high speeds. When queues occur on Route 33 eastbound, they prevent vehicles from exiting the circle onto Route 34 southbound by using the inside lane which requires them to make lane changes at a high speed within a short amount of time. These maneuvers often lead to collisions. Another problem is that the roadway in this area is wide enough to allow for three lanes, although it is designed to accommodate only two. When queues for Route 33 eastbound begin extending back to the Route 34 southbound exit, vehicles begin using this roadway as three lanes in order to dodge around the queue. This adds to the problem of the sideswiping collisions. A possible solution to this problem is to decrease the roadway width in such a way that also increases the exit curvature onto Route 34 southbound at this location. The decreased roadway width prevents drivers from using this section of roadway as three lanes. The increased exit curvature forces drivers to exit the facility at slower speeds, reducing the number of high-speed lane changes.

Speed Limit

A major problem leading to collisions at Collingwood Circle is the fact that the speed limit on each of the approaches is very different. For example, the posted speed limit on the Route 34 northbound and the Route 33/34 southbound approaches is 50-mph, while the speed limit on the Route 33 westbound approach is 45-mph, and the speed limit on the Route 547 eastbound approach is 35 mph. This creates a greater relative difference in speeds between movements in the traffic circle, leading to greater risk of collision. This can be seen in the presence of frequent collisions at the entrances and exits where vehicles are traveling at different speeds. These collisions can be reduced by decreasing the speed limit to 35 mph on all approaches in advance of the traffic circle.

It is important to note, however, that simply reducing the speed limit on the approaches will not necessarily reduce the speeds by a significant amount. There needs to be a perceived need by the drivers for speeds to be reduced accompanying the reduction in speed limits. Therefore, reduction of the speed limit should be accompanied by reduction of the roadway width on the approach and/or introduction of a curve approaching the circle to require vehicles to reduce speeds upon approach.

Advance Warning Signs

Another problem with the current design of Collingwood Circle is that drivers are able to enter the traffic circle and leave without taking much notice to ever having been in a traffic circle at all, especially when entering from Route 33/34 continuing to Route 34 southbound or entering from Route 33 continuing to Route 33/34 northbound. Advance warning signs stating “Traffic Circle Ahead” should be placed on all approaches in advance of the traffic circle. These signs should be accompanied by “Reduce Speed Now” signs to encourage drivers to slow down approaching the circle.

In addition to not recognizing that a traffic circle is ahead, drivers often do not know which lane they should use in order to make their desired movement through the circle. Placement of map-like navigation signs on each approach in advance of the traffic circle could reduce this problem. An example of this type of sign is shown in Figure 7 below.

Figure 7. Directional traffic sign

Right-of-way

Another issue with Collingwood Circle is that entering traffic has the right-of-way on all approaches except the Route 547 eastbound approach where entering traffic yields to circulating traffic. This allows vehicles to enter the circle at very high speeds, while traffic inside the circle is traveling at low speeds. This speed differential creates a higher risk of collisions. Also, requiring vehicles to stop or yield in the circulating roadways leads to queues and greater accident risk in the traffic circle. The presence of frequent rear-end collisions on the yield lines, especially where Route 34 northbound yields to Route 33 westbound exiting traffic, further proves this point. From an operational standpoint, having queues inside the traffic circle can create significant delays as opposed to leaving queues on the approach. For example, if a queue occurs within the traffic circle, this queue can back around the entire circle causing gridlock. However, if queuing occurs on an approach, operations can be maintained on the remaining approaches. From a safety perspective, when a rear-end collision occurs at a yield point inside the circle, gridlock and further collisions are likely to occur.

However, if this collision occurs on the approaching roadway, a queue is created on that approach, but traffic elsewhere continues moving smoothly. Therefore, a solution to the issue of right-of-way would be to give the right-of-way to the circulating traffic and place yields on the approaches.

Not only does giving the right-of-way to circulating vehicles reduce the risk of rear-end collisions at conflict points inside the circle, it also requires vehicles entering to slow down in order to yield to circulating traffic. This thereby, reduces overall speeds in the facility and reduces the relative difference in speeds between circulating, entering, and exiting traffic.

Striping

As previously mentioned, Collingwood Circle contains no striping within the traffic circle itself. This creates some confusion as to which lanes a driver is able to use to make a desired movement. In addition, it creates confusion over how many lanes the circle actually contains. At times, drivers use the circle as though it contained three lanes, while at other times the circle is used as though it contained two lanes. The lack of striping forces drivers to vie for positions in the circle, which leads to several sideswiping collisions, particularly at the diverge of Route 34 southbound and Route 33 eastbound. Striping indicating lanes usage may reduce such collisions. An example of a potential striping pattern for the circle is shown in **Figure 8** below.

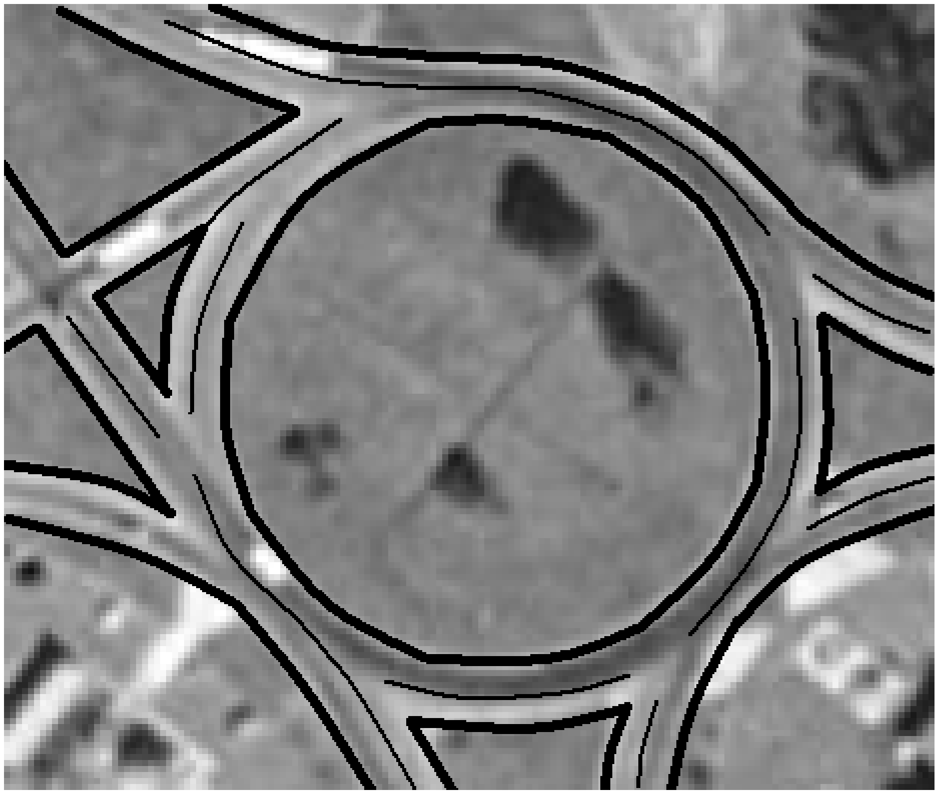


Figure 8. Striping pattern for Collingwood circle

Empirical Analysis

Following after, and supplementing the safety analysis based on the collision diagrams is an assessment based on the empirical models that predict accident frequencies. These models, developed by Maycock and Hall (1984) and Arndt (1998) were described in the *Review of Safety Models* chapter.[1,10]

Maycock & Hall (1984) [1]

In the case of Maycock and Hall, predictions of accident frequencies are presented here for both the existing conditions and the scenario, which corresponds to the geometric improvements suggested by NJDOT.

As can be deduced by reviewing the description of Maycock and Hall's model, predictions of the accident frequencies is dependent upon a number of inputs: the entry (Q_e), conflicting (Q_c), and exiting (Q_{ex}) flows, expressed as AADTs; the curvature (C_e) of the entry (reciprocal of the radius), the entry width (e), the approach width (v), the approach curvature category (C_a), the ratio of the inscribed diameter to the diameter of the central island (R), the percentage of motorcycles in the approach traffic stream (P_a), the angle to the next downstream entry (θ), the gradient category (g), and the sight distance on the approach (V_r). The values of these parameters for each of the approaches in the existing conditions are shown in Table 8 below.

Table 8. Geometric parameter values for the existing conditions

Location	Qe	Qc	Qex	Ce	e	v	Ca	R	Pm	Θ	g	Vr
33 EB/ 34 SB	20.676	1.05	18.70	0.00	8	8	0	1.21	5	24	0	500
547 NB	2.932	21.70	1.97	0.02	7	6	1	1.21	5	92	0	500
34 NB	11.924	9.28	13.00	0.02	8	8	1	1.21	5	83	0	500
33 WB	11.672	12.20	8.69	0.01	7	7	1	1.21	5	161	0	500

The AADTs are in thousands. The angle is expressed in degrees. The sight distances are set to 500 m indicating that they are effectively infinite.

The reconfiguration proposed by NJDOT is shown in the figure below. The stop-controlled intersection has been removed; radii have been decreased for three of the entrances; and the yields have all been moved to the approaches. No yields remain on the circulating roadway.

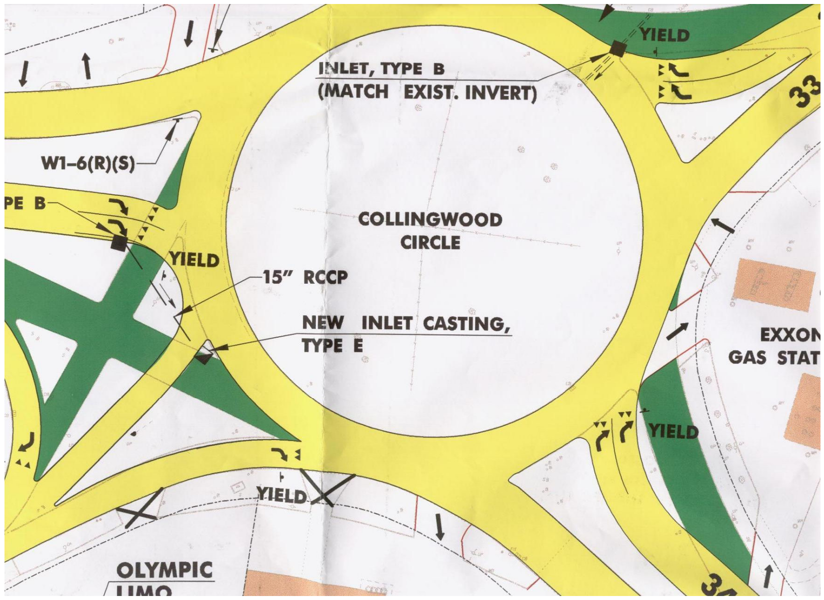


Figure 9. Geometric enhancements proposed by NJDOT

For the reconfigured facility proposed by NJDOT, the safety model inputs are as shown in the table below, to the best of the research team's ability to develop these values in the absence of a scaled drawing.

Table 9. Safety model inputs for the reconfigured facility proposed by NJDOT

Location	Qe	Qc	Qex	Ce	e	v	Ca	R	Pm	Θ	g	Vr
33 EB/ 34 SB	20.676	3.03	18.70	0.07	8	8	2	1.21	5	64	0	500
547 NB	2.932	21.70	1.97	0.02	7	6	1	1.21	5	77	0	500
34 NB	11.924	9.28	13.00	0.03	8	8	2	1.21	5	77	0	500
33 WB	11.672	12.20	8.69	0.03	7	7	1	1.21	5	142	0	500

The most notable change is to the entry curvatures, which are all smaller. This reflects the tighter radii, as can be observed in Figure 9. The angles between the approaches have also changed and the conflicting volume at the 33 EBD / 34 SBD approach is larger because the traffic exiting onto 547 SBD is now part of the conflicting volume at that entry.

Table 10 presents a comparison of the accident rates predicted by Maycock and Hall (1984) for the existing and enhanced conditions. It should not be expected that the accident rates would match the observed performance of the traffic circle. The equations are calibrated for British conditions, not U.S.; and they are for four-leg, single lane roundabouts; not multi-lane traffic circles. That having been said, examining the predictions is still valuable, especially the changes in those predictions based on the geometric enhancements proposed.

Table 10. Estimated accident rates based on Maycock & Hall

Approach Location	Existing	Enhanced	% Change	Existing	Enhanced	% Change
		Entering/Circ			Single Vehicle	
33 EB/ 34 SB	0.647	0.047	92.7%	0.542	1.873	-245.6%
547 NB	0.175	0.198	-13.1%	0.087	0.087	0.0%
34 NB	0.303	0.169	44.2%	0.443	0.541	-22.1%
33 WB	0.199	0.129	35.2%	0.324	0.457	-41.0%
		Approach-RearEnd			Other	
33 EB/ 34 SB	0.810	3.219	-297.4%	0.091	0.198	-117.6%
547 NB	0.039	0.039	0.0%	0.200	0.200	0.0%
34 NB	0.443	0.613	-38.4%	0.300	0.300	0.0%
33 WB	0.435	0.587	-34.9%	0.362	0.362	0.0%

The entry-circulating accident rates are predicted to decrease substantially, principally because of the major changes in geometry. The approach accident rates mostly increase, for the same reason that the entry-circulating rates decreased, because of the change in geometry. If the curvature of the 33 EBD / 34 SBD approach was not quite so sharp, the entry-circulating accident rate prediction would increase, but the approach accident rate prediction would decrease. (That's a minor modification that NJDOT might want to consider.) The single vehicle accident rates increase because of the greater curvature on the approaches. For all but the 33 EBD / 34 SBD approach, those increases are small. The increase for that approach could be mitigated if the radius on that approach was increased.

Arndt (1998)[10]

Arndt's (1998) model is very different from Maycock and Hall (1984). It is predicated on different data and structured in a different way. The accident rate predictions are not likely to be the same. It has not been calibrated for US conditions and it is intended to be used for roundabouts, not traffic circles.

The analysis for the existing conditions is shown in the table below.

Table 11. Accident rates for the existing conditions based on Arndt [10]

Entering/Circulating

Location	Ae	Qa	Nc	S(Qci)	Sra	tGa	Sri	tGi	dGi	Sci
33 EBD / 34 SBD	0.058	20.676	2	1.0521	10	1.2	10	1.2	10	30
547 NBD	0.081	2.9321	2	21.728	10	1.2	10	1.2	10	30
34 NBD	0.110	11.924	2	9.2797	10	1.2	10	1.2	10	30
33 WBD	0.122	11.672	2	12.247	10	1.2	10	1.2	10	30

Approaching Rear-End

Location	Aar	Qa	S(Qci)	Sa	Na
33 EBD / 34 SBD	0.340	20.676	1.0521	64	2
547 NBD	0.003	2.9321	21.728	40	1
34 NBD	0.651	11.924	9.2797	64	2
33 WBD	0.757	11.672	12.247	64	2

Single Vehicle

Location	Asv	Asa	Q	L	S	∆S	R
33 EBD / 34 SBD	0.001	0.0108	20.676	10	64	10	500
547 NBD	0.001	0.0032	2.9321	10	40	10	65
34 NBD	0.016	0.0236	11.924	10	64	5	56.6
33 WBD	0.014	0.0228	11.672	10	64	10	71

Exiting/Circulating

Location	Ad	S(Qci)	S(Qei)	Sra	Sri	dGi	Sci
33 EBD / 34 SBD	0.001	1.0521	18.67	10	10	10	30
547 NBD	0.001	21.728	1.9747	10	10	10	30
34 NBD	0.002	9.2797	13.04	10	10	10	30
33 WBD	0.002	12.247	8.6889	10	10	10	30

The variable labels are as follows. A_* denotes an accident rate prediction; Q_a is the approach volume (as an AADT); N_c is the number of circulating lanes; $S(Q_{ci})$ is shorthand for the conflicting volume at a given approach; S_{ra} is the average relative difference in 85th percentile speeds between the approach and the circulating traffic; t_{Ga} is the average time to get from the yield line to the conflict point; S_{ri} and t_{Gi} are identical thoughts for specific approaches; d_{Gi} is the distance in meters from the yield line to the conflict point; N_a is the number of lanes on the approach; L is the length in meters of the horizontal segment for which the single vehicle accident rate is being predicted; S is the 85th percentile speed at the beginning of that segment; ?S is the change in 85th percentile speed occurring across the segment; and R is the radius in meters of the segment. Table 12 below presents exactly the same information for the enhanced geometric conditions proposed by NJDOT.

Table 12. Accident rate predictions for the enhanced geometry

Entering/Circulating

Location	Ae	Qa	Nc	S(Qci)	Sra	tGa	Sri	tGi	dGi	Sci
33 EBD / 34 SBD	0.035	20.676	2	3.0269	5	1.2	5	1.2	10	30
547 NBD	0.031	2.9321	2	21.728	5	1.2	5	1.2	10	30
34 NBD	0.042	11.924	2	9.2797	5	1.2	5	1.2	10	30
33 WBD	0.047	11.672	2	12.247	5	1.2	5	1.2	10	30

Approaching Rear-End

Location	Asp	Qa	S(Qci)	Sa	Na
33 EBD / 34 SBD	0.171	20.676	3.0269	48	2
547 NBD	0.003	2.9321	21.728	40	1
34 NBD	0.165	11.924	9.2797	48	2
33 WBD	0.192	11.672	12.247	48	2

Single Vehicle

Location	Asp	Asa	Q	L	S	∆S	R
33 EBD / 34 SBD	0.523	0.1055	20.676	10	64	10	15
547 NBD	0.001	0.0032	2.9321	10	40	10	65
34 NBD	0.055	0.0356	11.924	10	64	5	30
33 WBD	0.053	0.0361	11.672	10	64	10	35

Exiting/Circulating

Location	Ad	S(Qci)	S(Qei)	Sra	Sri	dGi	Sci
33 EBD / 34 SBD	0.000	3.0269	18.67	5	5	10	30
547 NBD	0.000	21.728	1.9747	5	5	10	30
34 NBD	0.000	9.2797	13.04	5	5	10	30
33 WBD	0.000	12.247	8.6889	5	5	10	30

The things that have changed are: the radii on the approaches, the 85th percentile speeds, and the differences in the 85th percentile speeds. The next table presents the accident rates that are predicted by Arndt's (1998) model or both the existing conditions and the new NJDOT design. As can be seen, the entering / circulating accident rates decrease significantly, consistent with the predictions of Maycock and Hall, even though the numerical values are different. The approach-rear end accident rates are predicted to decrease, because of slower speeds on the approaches. The single vehicle accident rates are predicted to increase, but that is for the same reason that the other accident rates decreased – the curvature on the approaches has been increased. The exiting/circulating exit rates have fallen to near zero, because of the assumed reduction in the difference between the 85th percentile speeds - 5 km/hr instead of 10 km/hr.

Table 13. Accident rates that are predicted by Arndt's (1998) model

Approach Location	Existing	Enhanced	% Change
	Entering/Circulating		
33 EBD / 34 SBD	0.058	0.035	39.7%
547 NBD	0.081	0.031	61.7%
34 NBD	0.11	0.042	61.8%
33 WBD	0.122	0.047	61.5%
	Approach-RearEnd		
33 EBD / 34 SBD	0.34	0.171	49.7%
547 NBD	0.003	0.003	0.0%
34 NBD	0.651	0.165	74.7%
33 WBD	0.757	0.192	74.6%
	Single Vehicle		
33 EBD / 34 SBD	0.001	0.523	-52200.0%
547 NBD	0.001	0.001	0.0%
34 NBD	0.016	0.055	-243.8%
33 WBD	0.014	0.053	-278.6%
	Exiting/Circulating		
33 EBD / 34 SBD	0.001	0.000	100.0%
547 NBD	0.001	0.000	100.0%
34 NBD	0.002	0.000	100.0%
33 WBD	0.002	0.000	100.0%

Table 14. Percent difference in accident rates between alternatives

	Maycock & Hall	Arndt
ACCIDENT TYPE	1→2	1→2
Entering/Circulating	59.0%	58.2%
Approach-Rear-End	-158.1%	69.7%
Single Vehicle	-111.9%	-1875.0%
Other	-11.2%	100.0%
Total Percent Change	-67.0%	39.0%

0.xxx = higher (worse) accident rates predicted, negative percent change
0.xxx = best improvement among alternatives
* These percent changes are adjusted from the raw percent changes to account for the undefined accident rates shown in the previous table.

Modeling the Treatments for Simulation

The safety treatment options discussed above are all easily modeled using the PARAMICS computer software package. However, PARAMICS has many limitations when it comes to modeling the effects of certain geometric parameters. For example, the roadway width may be altered or superelevation imposed on the circulating roadway in the traffic circle. In the real world environment, these treatments would both have a significant impact on speeds in the facility. However, PARAMICS is unable to model these effects as a direct result of changing the geometry. What PARAMICS does allow the user to do is input a given percent speed reduction that would be anticipated due to the presence of a curve. Therefore, when modeling the treatments above, a percent speed reduction must be entered to reflect the impacts of making such a change.

Three scenarios were developed for improvements to Collingwood Circle. The existing conditions served as “Case 1”. “Case 2” reflected the improvements suggested by NJDOT, which include realigning the Route 33/34 southbound approach and the Route 547 exit from the circle to eliminate the stop-controlled intersection on the Route 547 exit, and giving the right-of-way to circulating traffic and placing yields on the approaches. “Case 3” is a collection of minor improvements intended to alter speeds and headways in the traffic circle without making major geometric changes. This case includes posting advance warning signs on each approach to indicate that a circle is ahead, which lane to use, and which exit to use; reduction of speed limit on all approaches and within the circle; striping to indicate proper lane usage and reduce driver confusion. “Case 4” includes geometric changes intended to have a larger impact on speeds, which include reduction of entry width and circulating roadway width, reduction of speed limit on all approaches and within the circle, imposing reverse superelevation, increase entry path curvature on Route 34 northbound and Route 33/34 southbound approaches, striping to indicate proper lane usage and reduce driver confusion.

Each of the four cases has been modeled in PARAMICS and analyzed using four output metrics: speed distribution at location, speed trajectories, gap acceptance distribution, and headway distribution. Speed distribution was used to measure the variability in speeds at the conflict points. In an ideal situation, one would like to see a narrow distribution of speeds, indicating that entering, exiting and circulating speeds are all approximately equal. Unsafe conflict points occur where there are large differences in speeds. Speed trajectories were used to indicate how vehicle speeds change as a vehicle navigates through the traffic circle. Ideally, one would like to see a gradual decrease in speed as the vehicle approaches the facility, a constant speed throughout the facility, and a gradual increase in speeds as the vehicles exit the facility. When large increases or decreases in speed occur within the facility, this indicates that queuing may be occurring or that vehicles may be traveling at unsafe speeds. Gap acceptance distributions were used in combination with speeds to sense the safety of a given conflict point. For example, at a high-speed location, vehicles require larger gaps in order to merge with traffic. At a low speed location, vehicles require shorter gaps. In addition, where speeds are high on the conflicting roadway, there tends to be less variability in the gaps accepted. When speeds are low on the conflicting roadway, there is larger variability in the gaps accepted due to the wider range of available safe gaps. The headway distribution at the conflict points was also used as an indicator of safety. Where a random headway distribution occurs, traffic is likely to be free flowing. However, if a situation occurs with two peaks in the headway distribution plot, this may indicate that something is occurring at this location to restrict free-flow. With this brief overview now complete, detailed simulation results of select locations are now discussed.

Route 34 Southbound Exit

The Route 34 southbound exit is one place where a significant difference in speeds exists. At this location, the roadway is extremely wide and drivers become confused over which lane to use to exit or circulate in the roadway. In addition, the yield on the circulating roadway at the Route 34 northbound entrance to the facility often creates a queue that extends into the Route 34 southbound exit, causing vehicles to dodge around one another and use this section of the roadway as a three-lane section. The intent of the safety treatments mentioned above is to eliminate this situation and reduce overall speeds and the variability in speeds at this location and other locations within the facility. Figure 10 and Figure 11 below show the speed distribution at the Route 34 southbound diverge location as it exists today based on the simulation model outputs.

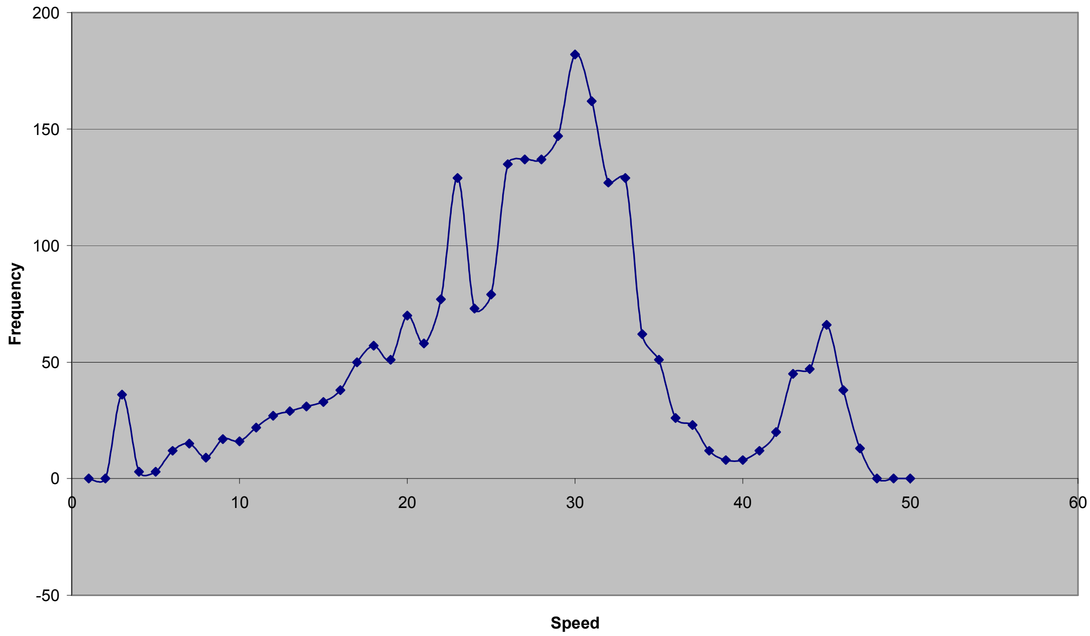


Figure 10. Speed Distribution at Route 34 SB Diverge – Existing Conditions

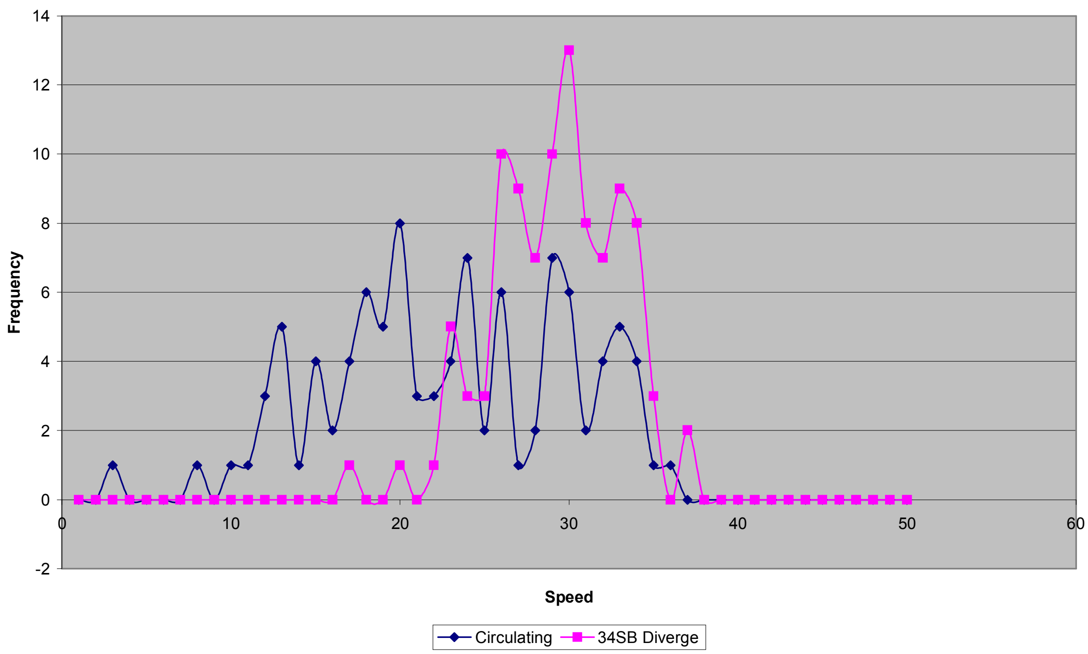


Figure 11. Speed Distributions at Route 34 SB Diverge – Existing Conditions

As the above figures indicate, there is a great deal of variability in the speeds at this location. In addition, the speed of traffic diverging onto Route 34 southbound is significantly higher than the speed of the circulating traffic. Figure 12 below shows the speed distribution at the same location for Case 2, which has the geometric improvements proposed by NJDOT.

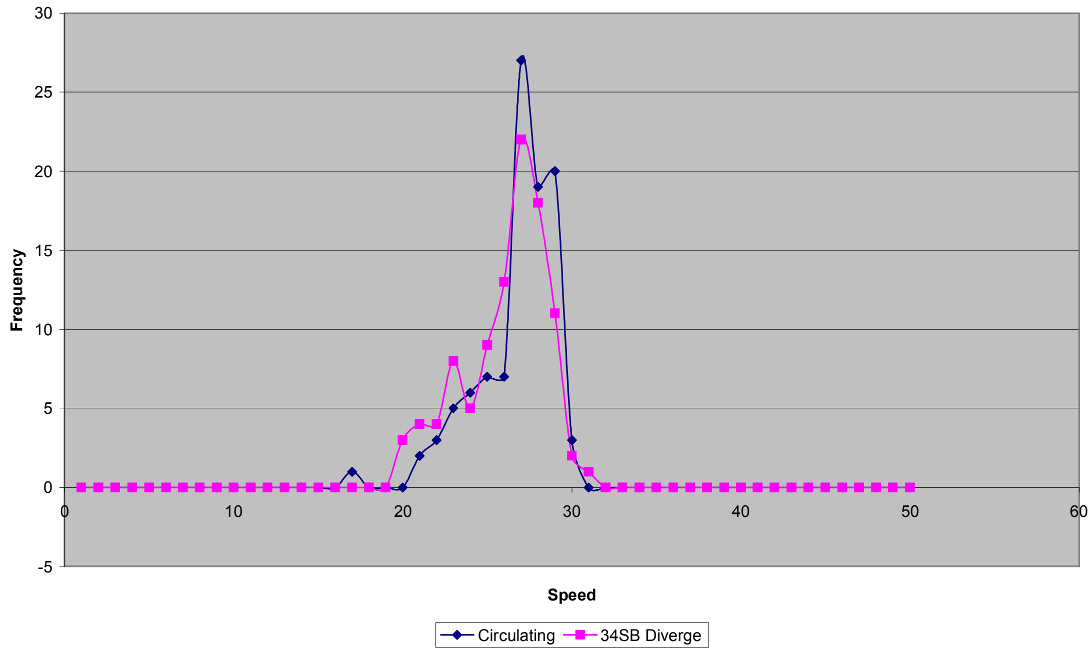


Figure 12. Speed Distributions at Route 34 SB Diverge – Case 2 (NJDOT)

As Figure 12 makes apparent, upon implementation of the improvements proposed by NJDOT, the overall speeds at the Route 34 southbound diverge should be reduced and the variability in speeds at this location should also be reduced. In this situation, PARAMICS is capable of reflecting the changes in speed that would result from making the geometric improvements included in this case.

Figure 13 and Figure 14 present the speed distribution at this same location for Cases 3 and 4. It is clear that the improvements associated with these alternatives do not produce nearly as good a result as the changes suggested by NJDOT.

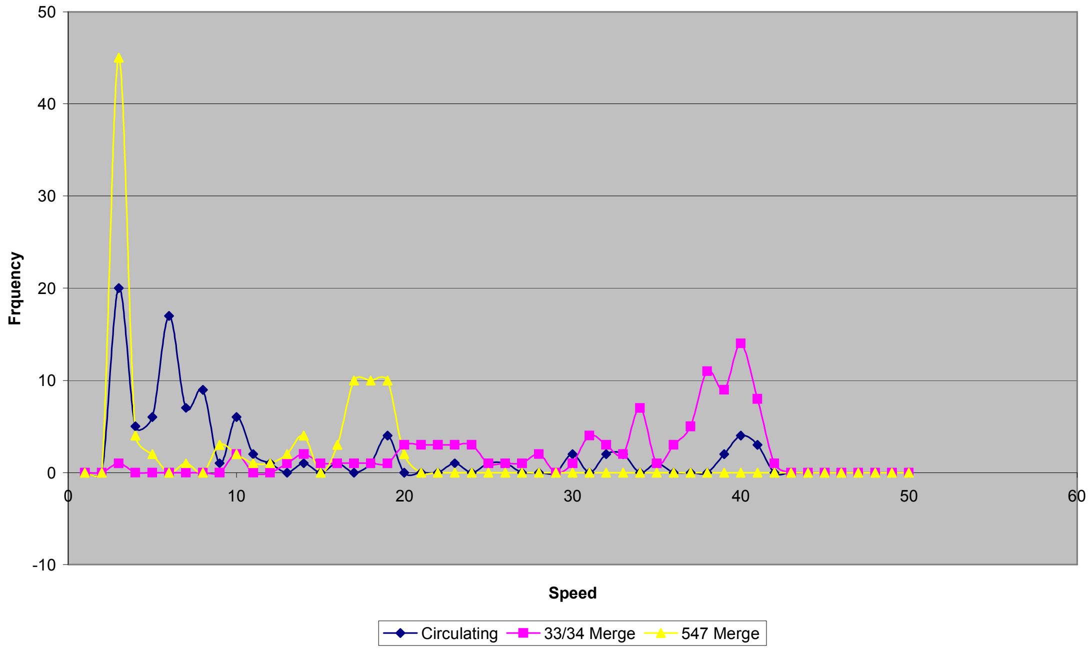


Figure 13. Speed Distributions at Route 34 SB Diverge – Case 3

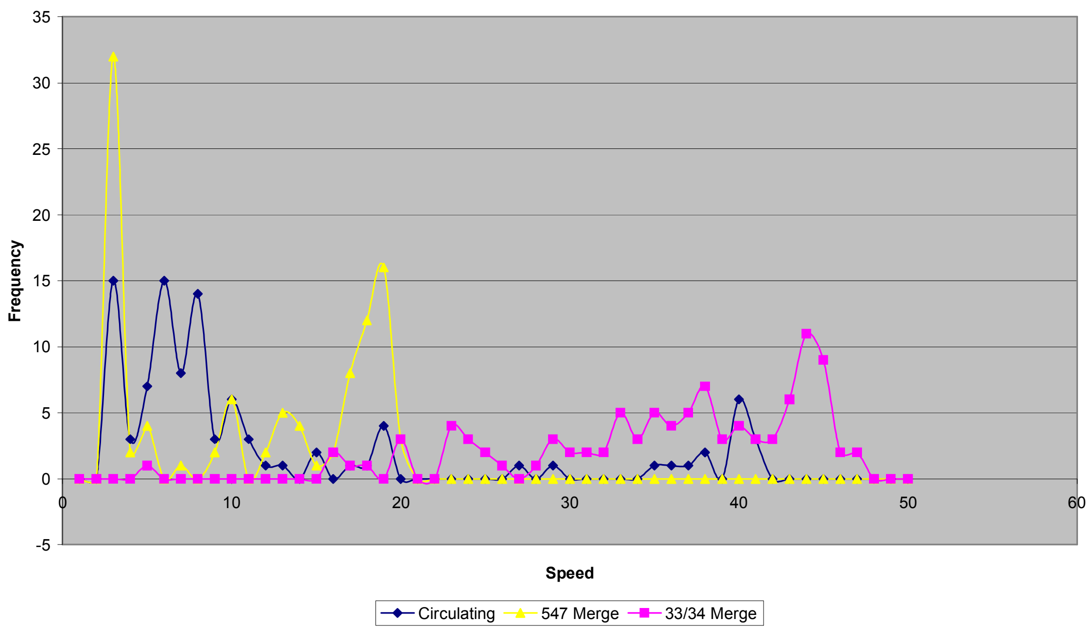


Figure 14. Speed Distributions at Route 34 SB Diverge – Case 4

Route 547 Eastbound Merge with Routes 33/34 Southbound

Another location where speeds and variability in speeds is an issue is on the Route 33/34 south approach to the traffic circle. Here, circulating traffic within the circle, Route 33/34 southbound and Route 547 eastbound traffic all merge in one location with Route 33/34 traffic having the right-of-way. During peak periods, Route 33/34 traffic is typically traveling very fast, while traffic on the circulating roadway and on Route 547 must stop and wait for an opening in the Route 33/34 traffic. Figure 15 below shows the speed distribution at this location under existing conditions. As indicated in the graph, there are three very distinct peaks in the speeds occurring at this location. Route 33/34 traffic tends to be traveling as speeds of 45-50 mph, while Route 547 traffic tends to travel at speeds of 15-20 mph. The traffic on the circulating roadway is traveling at speeds of approximately 10 mph.

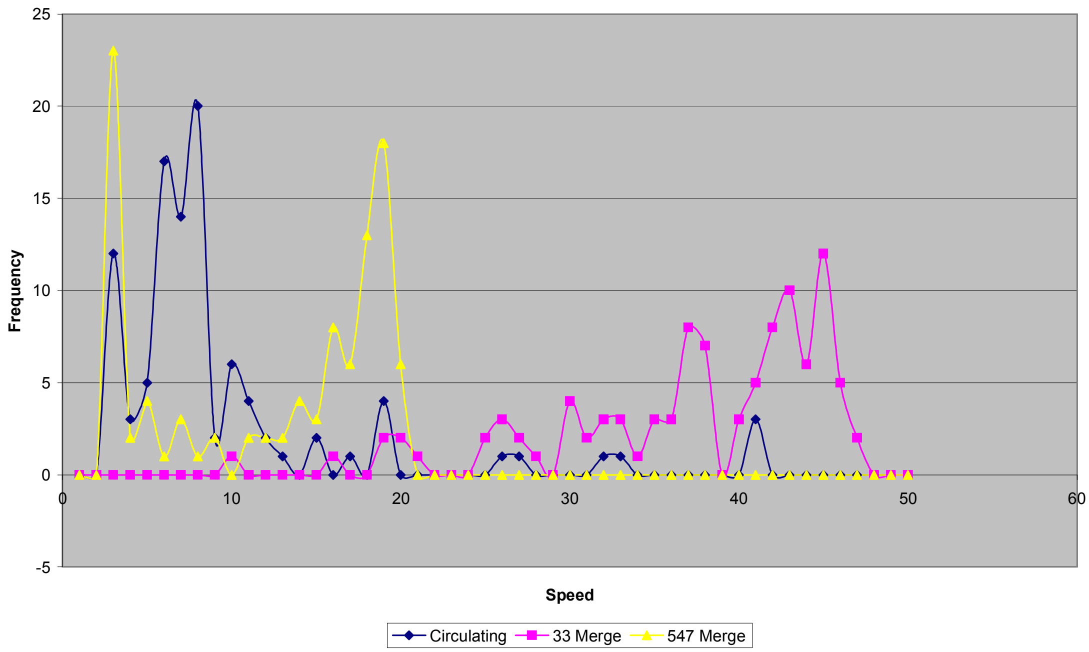


Figure 15. Speed Distribution at Route 33/34/547 Merge – Existing Conditions

Figure 16 and Figure 17 below show the speed distributions that are likely to occur at the Route 33/34 and Route 547 merge locations for Case 2, which incorporates the improvements proposed by NJDOT. As is apparent in the graphs, the overall speeds have been significantly reduced, and speeds of traffic on Route 33/34 have been reduced to roughly 20-30 mph. The variability in speeds at the merge locations has also been significantly reduced, as circulating traffic now also travels at speeds of 20-30 mph.

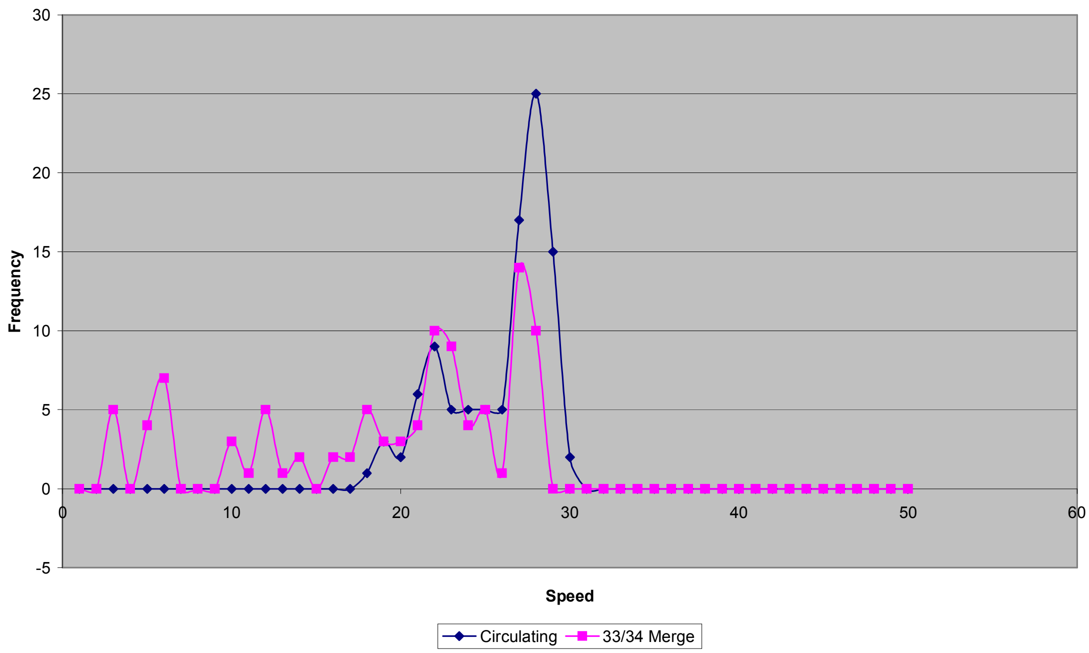


Figure 16. Speed Distributions at Route 33/34 Merge – Proposed Condition

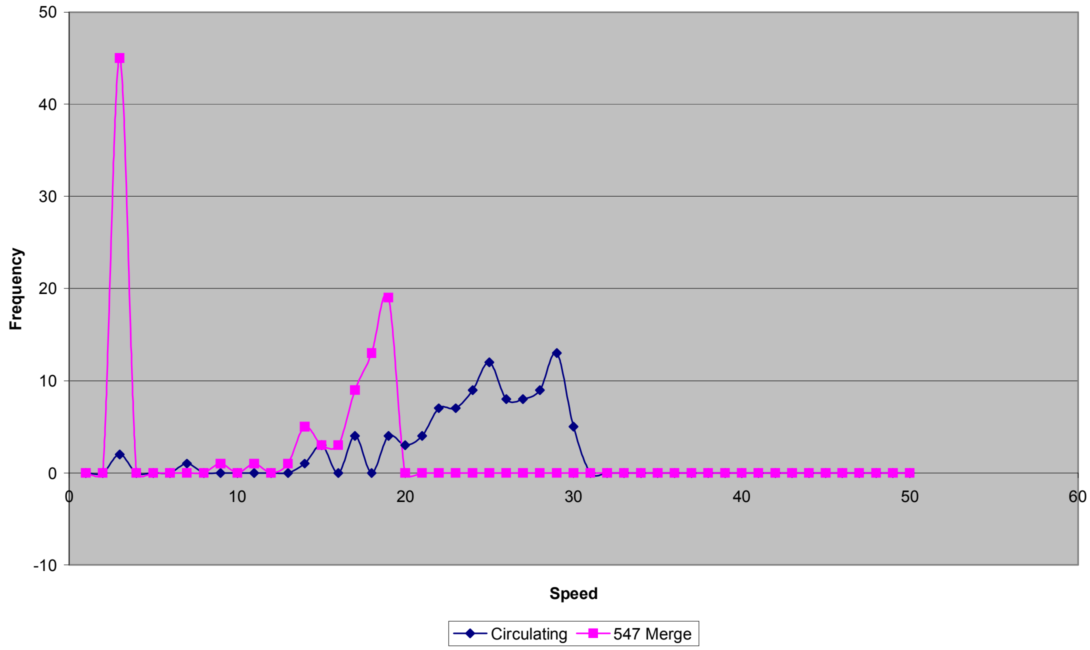


Figure 17. Speed Distributions at Route 547 Merge – Proposed Condition

While speeds at the conflict points are important from a safety perspective, it is also important to look at changes in speeds as vehicles travel through the facility. Therefore, speed trajectories were examined for each origin-destination pair in the traffic circle to look at how vehicles travel through the circle. The example shown below is for vehicles entering on the Route 34 northbound approach and exiting onto Route 547 westbound. Figure 18 below shows the speed trajectory of vehicles making this movement under existing conditions.

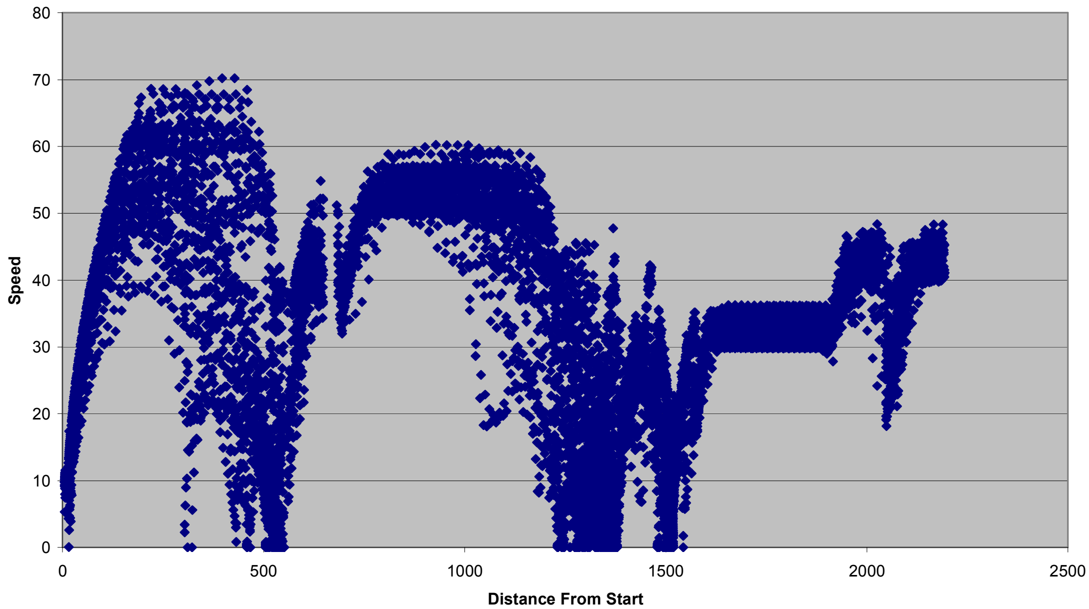


Figure 18. Speed trajectory, route 34 NB to 547 WB – existing conditions

It is important to note that the PARAMICS model used to obtain these speed profiles included intersections in the vicinity of Collingwood Circle. Therefore, the section of the plot that actually reflects speeds in the circle is the section ranging from 1000 ft to 1700 ft on the “Distance From Start” scale. As indicated by the graph, there are two locations within the circle where traffic comes to a stop or near-stop. These locations are where the circulating traffic yields to traffic entering on Route 33 westbound and where traffic exiting onto Route 547 yields to traffic entering on Route 33/34 south. As also indicated in this graph, there is a great deal of variability in speeds in the circle, particularly between the Route 34 northbound and Route 33 westbound approaches where vehicles may stop to yield to entering traffic or may continue through the circle unimpeded.

Figure 19 below shows the speed trajectory of vehicles making the same movement under Case 2, which incorporates the improvements proposed by NJDOT. The speeds between 1,300 and 1,600 ft from the start remain fairly constant with limited variability, indicating that traffic is moving at a constant speed through the traffic circle, as one would like to see. There is also a gradual change in speed between 900 ft and 1,300 ft from the start point, indicating that traffic is slowing down as it approached the traffic circles. However, there is a great deal of variability as to when a vehicle begins to slow down while approaching the traffic circle. This indicates that a queue is likely to be occurring on the Route 34 northbound approach to the traffic circle. The location where a vehicle begins to slow down approaching the circle is an indication of the length of the queue at that particular time.

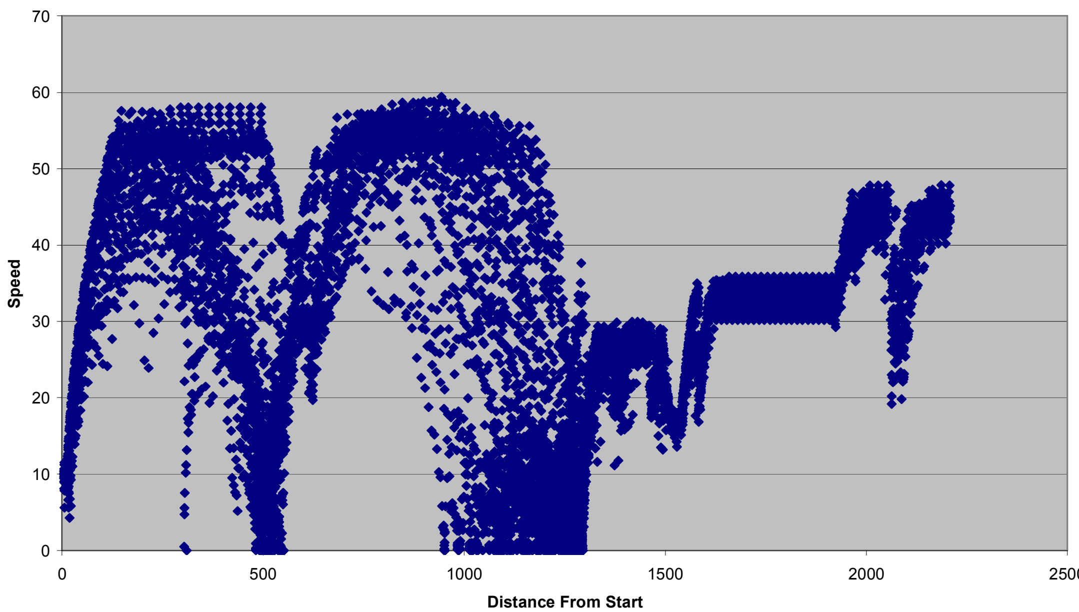


Figure 19. Speed profile, from route 34 NB to route 547 WB – Case 2

Figure 20 and Figure 21 present the results for Cases 3 and 4; and as was the case for the previous situation, the improvements associated with these cases are not as significant as for Case 2.

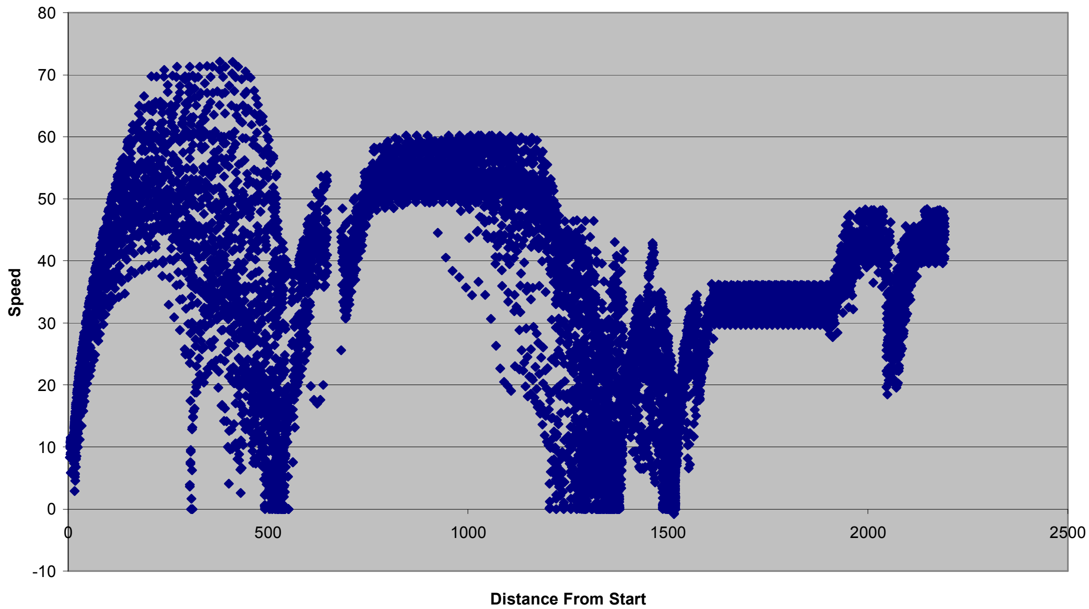


Figure 20. Speed profile, from route 34 NB to route 547 WB – Case 3

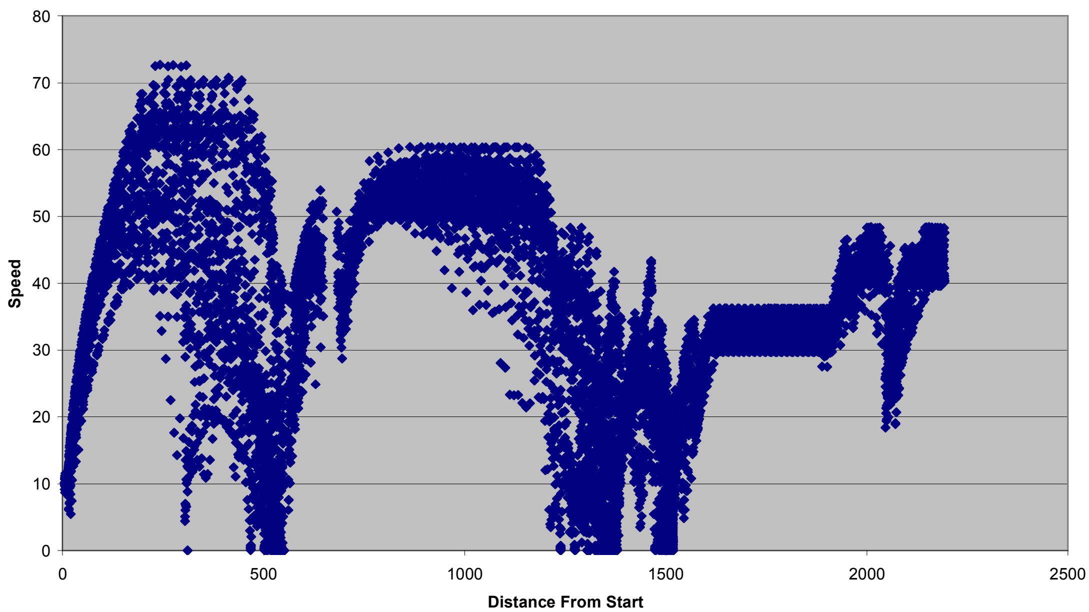


Figure 21. Speed Profile, From Route 34 NB to Route 547 WB – Case 4

Route 547 Westbound Merge with the Circulating Roadway

One location where a number of collisions occurred was where Route 547 westbound approaching traffic merges with the circulating roadway. Traffic at this location must yield to Route 33/34 southbound traffic and traffic already circulating within the facility. The traffic on Route 33/34 is often heavy and traveling at high speeds, which makes it difficult for vehicles to enter from Route 547. The high speeds of the Route 33/34 traffic require a large gap in traffic for vehicles to enter from Route 547. Often drivers become tired of waiting for long enough gaps and begin to accept unsafe gaps. It is under these circumstances that collisions often occur. Figure 22 below shows the gap acceptance distribution for vehicles entering the circle from Route 547 westbound under existing conditions. As shown in the graph, the majority of accepted gaps are in the range of 16 to 22 seconds. However, many much smaller gaps were also accepted, as mentioned above.

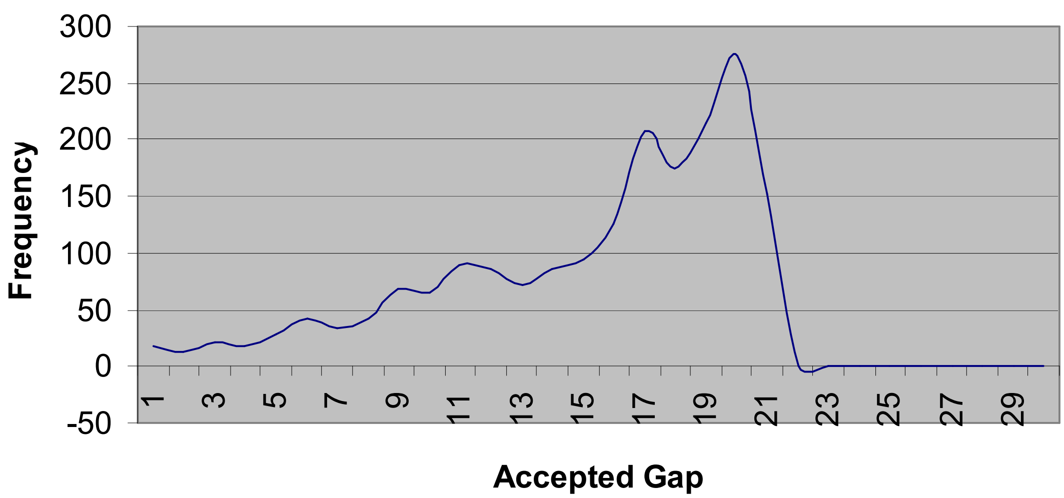


Figure 22. Gap Acceptance Distribution, Route 547 Enter – Existing Case

Figure 23 below shows the gap acceptance distribution at the same location for

Case 2, which involves the improvements proposed by NJDOT. As shown in the graph, the gaps accepted tend range from 9 to 14 seconds. This reduction in the length of gaps accepted indicates that speeds on the circulating roadway and on Route 33/34 southbound have been reduced. In addition, it is important to note that vehicles are no longer taking unacceptable gaps of less than 5 or 6 seconds. This indicates that more acceptable gaps exist, allowing vehicle to enter the circulating roadway more easily without having to take unsafe gaps.

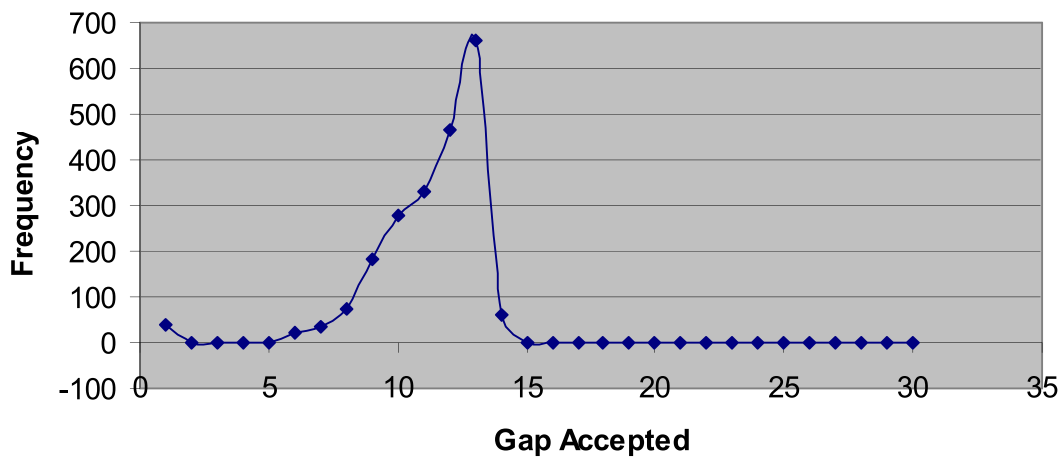


Figure 23. Gap Acceptance Distribution, Route 547 Enter – Case 2

As mentioned above, headways at the conflict points were also examined as an indicator of safety conditions and operations within the traffic circle. However, headway distributions remained fairly constant between scenarios. The lack of variation in headway distributions between scenarios may indicate a flaw in the ability of PARAMICS to model the impacts of various geometric changes. For example, if one were to introduce a curve on a roadway, there would likely be a countervailing increase in headways as vehicle become wary of traveling too close under dangerous driving conditions. However, PARAMICS is not capable of reflecting this change in headways.

Collingwood Circle Conclusions

This chapter included discussion and analysis of the safety-related conditions at the Collingwood traffic circle in New Jersey. The circle is assessed using a carefully developed safety analysis methodology. Both the empirical models and traffic simulations tested support the proposition that safety will be increased with implementation of the proposed treatments.

Brooklawn Circle Analysis

In this section, the Brooklawn circle is analyzed. The Safety Methodology chapter provides an overview of the process, which included the simulation analyses, the empirical analyses, comparison of these results and a benefit/cost analysis. At the end of this section there are recommendations for the Brooklawn Circle based on the quantitative and qualitative assessments.

Study Location

The Brooklawn traffic circle, located in Camden County, New Jersey, is actually comprised of two separate circles connected by a short connector passing under a railroad line.

The western circle has three legs and the eastern one has four legs. The southbound approach on the west circle is New Broadway Avenue; the northbound approach is US 130 North and the westbound approach is US130 South. On the western side of the circle is a local farm market. There is a yield sign on the New Broadway Avenue entrance but no yield signs anywhere else. There is no lane striping within the circle.

The eastern circle is more complex. The eastern approach is US 130 North, coming from the western circle. The northbound approach is NJ 47 North. Creek Rd intersects NJ 47 just prior to the traffic circle. The westbound approach is US 130 South and the southbound approach is Hannevig Avenue. On three of the segments between the legs there are commercial establishments with multiple driveways. The yield points are both on the circle and on the approaches. On the eastbound approach, the yield is on the entrance. For the northbound approach, the yield is on the circle. For the westbound approach, the yield is on the circle while for the southbound approach (Hannevig Ave), the yield is on the approach. There is no lane striping within the circle. As shown in Figure 24, the westbound approach (US 130 South) has a relatively long straight section before making a sharp right at the intersection of the circle. This promotes vehicles to continue to the circle at a high rate of speed until they reach the end of queue. This can be problematic for drivers unfamiliar to the facility, due to the fact that they may not be prepared slow and merge with oncoming traffic in the circle.

Accident History

Crash diagrams have been created for the two traffic circles based on the police reports provided by the NJDOT. These diagrams provide insights for each accident, such as the location, type of accident, time of day, weather conditions and severity. Based on the accident patterns, a set of proposed treatments have been developed. At this location the Delaware Valley Regional Planning Commission (DVRPC) also conducted studies.[32] Therefore their recommendations were also examined.

Eastern Circle

Between January 1, 2000 and December 31, 2002 there were 94 accidents associated with the eastern traffic circle. Figure 24 shows a collision diagram for this study period. Automobile accidents were 91 percent of the total. Commercial vehicles and buses were involved in the remaining 9 percent. Approximately 52 percent of the accidents occurred when the road conditions were wet or icy. Most of the accidents took place during daylight hours. The nighttime accidents are concentrated on the westbound approach, 75 percent of all the nighttime accidents took place at that location.

None of the accidents produced a fatality but there were 23 injuries. Injuries occurred approximately 21 percent of the time. The most problematic location was on the westbound (US 130 South) approach. Approximately 50 percent of all the accidents were related to vehicles entering on this approach. Other statistics related to the type of accidents encountered at the circle are:

- 37 of 94 (39%) involved “fixed object” collision
- 22 of 94 (23%) involved “same direction side-swipe” collisions
- 18 of 94 (19%) involved “angle” collisions
- 17 of 94 (18%) involved “rear-end” collisions

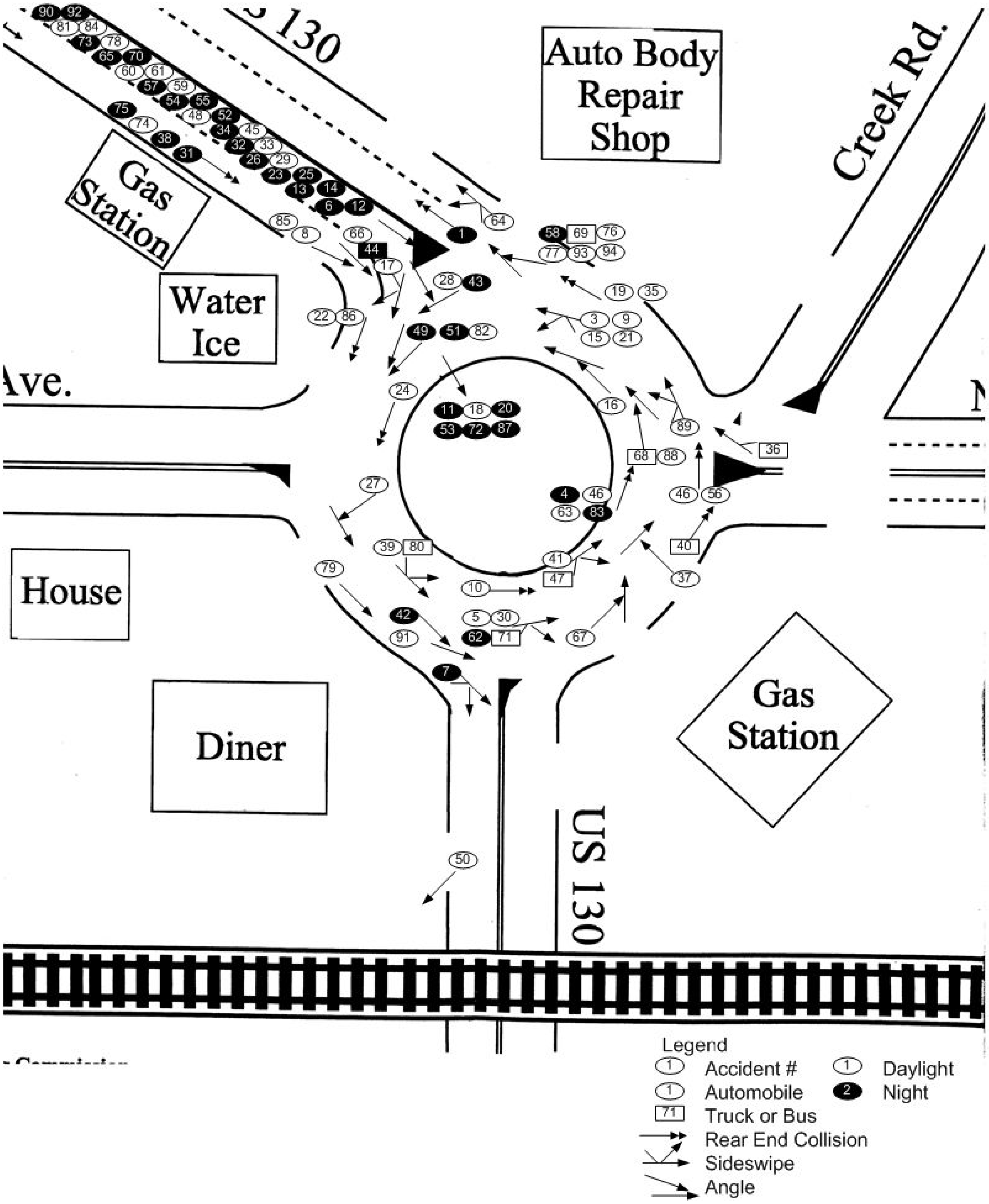


Figure 24. Brooklawn east crash diagram 2000 - 2002

The following countermeasures were investigated to reduce the risk of future incidents.

EASTERN CIRCLE, WESTBOUND APPROACH (US 130 SOUTH)

This is the most common location for accidents in the eastern circle. The most frequent accident involves vehicles striking the curb prior to merging onto the circulating roadway. There were 28 “fixed object” collisions between 2000 and 2002. Of these, 64 percent occurred during darkness. 85 percent of the 34 “fixed object” accidents on this approach occurred when the roadway was wet or icy. Six vehicles continued straight across the circle and struck something on the center island. Those accidents primarily occurred when it was dark and wet.

There were four “rear-end” collisions, two “angle” collisions and three “same direction side-swipe” collisions. The “rear-end” collisions occurred on the approach just upstream of the merge point of the circle. 75 percent of these collisions were during dark hours. Both of the “angle” collisions involved a vehicle approaching the circle at an unsafe speed. The “same direction side-swipe” collisions occurred between two vehicles that were entering the circle.

There were seven collisions between entering and circulating vehicles. Two of these were “rear-end” collisions and five “angle” collisions. The two “rear-end” collisions were produced by two vehicles entering the circle at the same time. Each of these incidents produced one person suffering minor injuries. Two of the “angle” collisions involved one vehicle failing to enter the circulating traffic, rather entering the circle as if entering a standard intersection. At this point a circulating vehicle was “t-boned.” The other three “angle” collisions involved merging vehicles colliding with circulating vehicles. These collisions were primarily due to driver inattention.

The Institute of Transportation Engineers publication Traffic Engineering Handbook (the Handbook) lists excessive speed, driver unaware of intersection, slippery surface, lack of adequate gaps, and crossing pedestrians as causes of "same direction rear-end" collisions at unsignalized intersections.[35] It also lists excessive speed and inadequate signing as possible causes of "same direction side-swipe" collisions. There are rarely pedestrians at this portion of the Brooklawn circle, so crossing pedestrians may be neglected. As effective countermeasures for these accident problems, the Handbook lists reducing speed limit, installing illuminated street signs, and installing advance guide signs to reduce "same direction side-swipe" collisions. The Handbook recommends reducing speed limit, installing or improving warning signs, and providing "slippery when wet" signs as effective countermeasures for "same direction rear-end" collisions. Based on the predictive model for approaching collisions by Maycock and Hall (1984), factors affecting the number of collisions on an approach are:

- Entry flow
- Entry path curvature
- Sight distance
- Entry width
- Gradient category

Therefore, effective geometric design treatments would include designs that improve these characteristics. According to Arndt's Australian model for approaching rear-end collisions, the main contributing factor is speed. Therefore, safety treatments designed to reduce speed should be applied.

EASTERN CIRCLE, WESTBOUND EXIT

The westbound exit (leading to the western traffic circle) had three "same direction side-swipe" collisions and two "angle" collisions between 2000 and 2002. Only one involved injuries. The main cause of the "same direction side-swipe" collisions was improper passing. One involved a tractor-trailer. In one of the rear-end collisions, a vehicle collided with the curb while driving at an unsafe speed.

Prior to the exit there were also several accidents. In one, a vehicle struck a pile of debris in the roadway. A “rear-end” collision occurred midway between the westbound entrance and the westbound exit. Also, just prior the exit there was a right angle collision that involved a vehicle traveling at an unsafe speed and spinning out of control striking the second vehicle.

Many of the accidents at this location were most probably due to improper lane changes. Brooklawn circle is wide enough for two lanes of traffic. However, no striping inside of the circle exists to suggest to drivers how they should navigate the facility. This leaves drivers confused as to whether they should navigate the circle in one or two lanes. Countermeasures for reducing “same direction side-swipe” and “same direction rear-end” recommended by the ITE Handbook are discussed in the section for the westbound approach.

EASTERN CIRCLE, EASTBOUND APPROACH

There were no reports of incidents occurring directly on the eastbound approach. However, there was one “rear-end” collision between two vehicles in the circulating roadway prior to reaching the merge point of the approach. In addition, four “same direction side-swipe” collisions took place on the circulating roadway at the merge point. One of these produced two minor injuries. The causes for these incidents included driver inattention, improper lane changing and failure to yield. Most of the accidents occurred during daylight hours when the roadway was dry.

EASTERN CIRCLE, NORTHBOUND ENTRANCE TO EASTBOUND EXIT

On the eastern section of the circle, between the NJ 47 entrance and the US 130 exit, there were approximately five accidents. Two of these were “angle” collisions caused by vehicles exiting the gas station located adjacent to the circle.

Driver inattention also caused two “same direction side-swipe” collisions, one involving a commercial vehicle.

EASTERN CIRCLE, SOUTHBOUND EXIT (NJ 47)

At the NJ 47 southbound exit there was one “rear-end” collision. This collision was due to a queue forming into the circle due to one vehicle turning left onto Creek Rd after exiting the circle.

EASTERN CIRCLE, NORTHBOUND ENTRANCE (NJ 47)

The accidents that occurred at the location of this approach included, six “rear-end” collisions, two “angle” collisions and one “same direction side-swipe” collision. Four people were injured in these nine accidents.

Driver inattention was the main contributing factor in approximately 78 percent of these collisions. Wet roads were a factor in approximately 50 percent. All of the “rear-end” collisions took place on the circulating roadway, just prior to the merge point.

EASTERN CIRCLE, US 130 NORTHBOUND EXIT

Approximately 15 accidents were associated with the US 130 northbound exit. Of these, 87 percent occurred between vehicles that were in the circulating roadway. Eighty-seven percent of the incidents occurred during daylight hours when the roadway was dry. The main cause for the accidents was driver inattention (80 percent of the time). Twenty percent of the accidents were caused by Improper passing and following to closely.

Western Circle

There were a total of 13 accidents for the western traffic circle, almost an order of magnitude less than for the eastern circle, between January 1, 2000 and

December 31, 2002. Figure 25 represents a collision diagram showing both daytime and nighttime crashes. The majority of the accidents took place during daylight hours (92%). Fifty-four percent (54%) of the accidents occurred when the road conditions were wet or icy. Eighty-five percent (85%) of the accidents involved autos alone. Fifteen percent (15%) of the accidents involved commercial vehicles or buses.

The 13 accidents did not produce any fatalities but there were eight injuries. Accidents with injuries occurred approximately 38 percent of the time. No location tended to have the most accidents, rather they were scattered. Other statistics related to the type of accidents encountered at the circle include:

- 5 of 13 (38%) involved “angle” collisions
- 4 of 13 (31%) involved “same direction side-swipe” collisions
- 3 of 13 (23%) involved “rear-end” collisions
- 1 of 13 (8%) involved “fixed object” collision

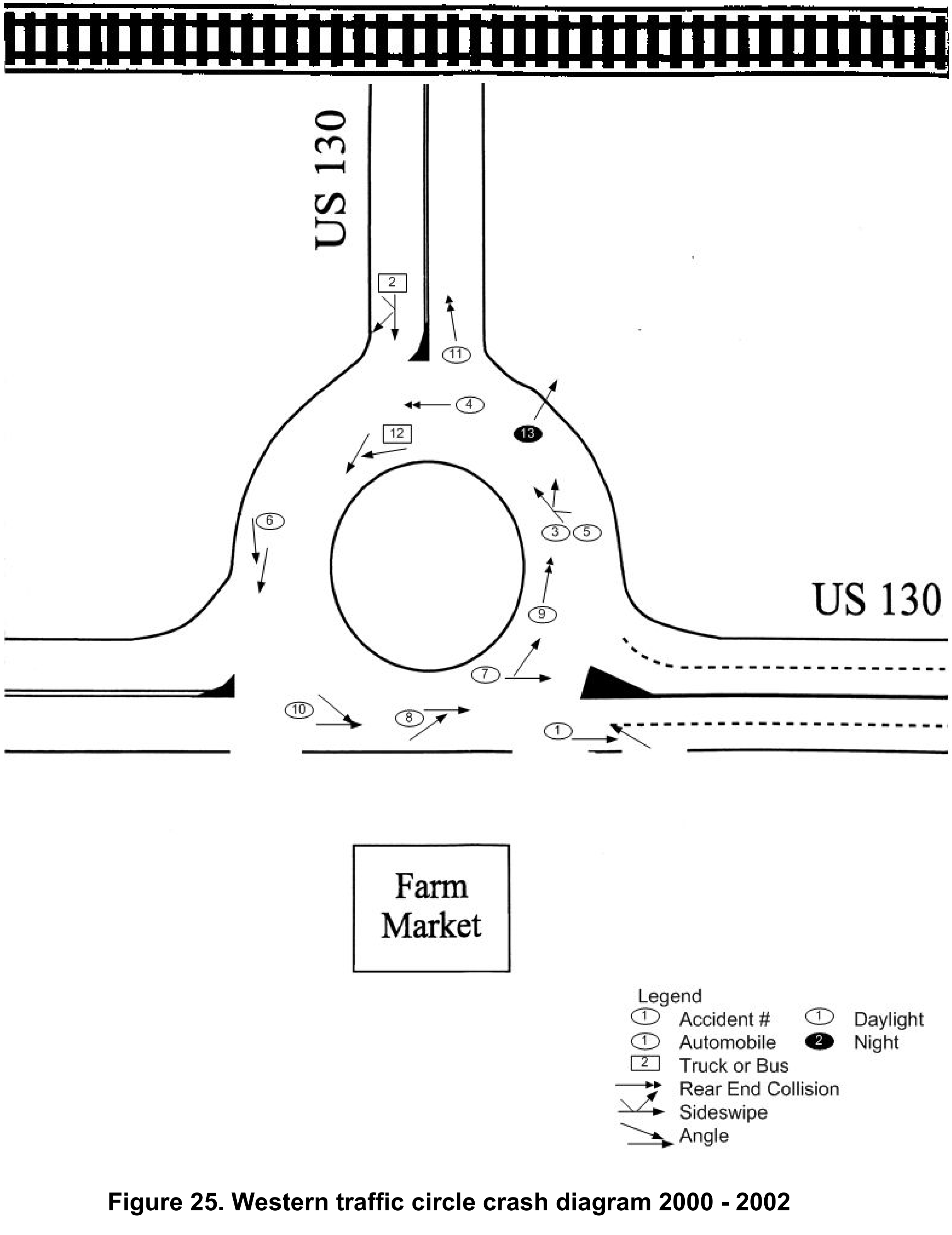


Figure 25. Western traffic circle crash diagram 2000 - 2002

Of the thirteen-recorded accidents at the western circle during the three-year time period few occurred at the same location. Most of all of the accidents at this circle occurred during the daylight hours. The majority of the accidents were also due to driver inattention therefore. Since most of the accidents occurred sporadically and no patterns could be developed detailed descriptions are not provided.

Selection of Safety Treatments

As a result of the of the accident history study, several safety treatments were developed as possibilities for the traffic circles. Those treatments are discussed in the following paragraphs.

Entry Curvature and Deflection

Entry curvature is a main variable contributing to approaching collision frequency. Approaching collisions are a problem particularly on the westbound approach on the eastern circle (US 130 Southbound) where 28 fixed object collisions, four "rear-end" collisions, two "angle" collisions and three "same direction side-swipe" collisions occurred. A main contributing factor to these collisions was high speeds.

Increasing the entry curvature and entry deflection on this approach should reduce speeds. However, there is limited space to realign the approach due to the proximity of local establishments. It would be possible to reconfigure the entire leg to provide some speed reduction. Increasing the entry curvature and entry deflection on the US 130 southbound approach would require vehicles to slow down entering and circulating the facility. In addition, it would require drivers to recognize that they have entered a traffic circle and force them to be more compliant with the rules of the traffic circle.

Advance Warning Signs

There is little signage warning the driver of the upcoming facility. Advance warning signs stating "Traffic Circle Ahead" should be placed on all approaches. These signs should be accompanied by "Reduce Speed Now" signs to encourage drivers to slow down. These signs should also be accompanied by amber flashing lights, especially during inclement weather and at night.

In addition, drivers often do not know which lane they should use to make their desired movement through the circle. Placement of map-like navigation signs on each approach should reduce this problem. An example of this type of sign is shown in Figure 26 below.

Figure 26. Directional traffic sign

Right-of-way

Another issue is that the right-of-way is not consistent on each approach. On the western circle the only yield control is located on the New Broadway Avenue approach. The other two junctions are unsigned. At the eastern circle the eastbound approach has a yield. However, at the northbound approach (NJ47), the yield is on the circle. The same is true for the westbound approach (US130 South). For Hannevig Avenue, the yield is on the approach. This causes confusion. Drivers have to recognize where they are in the circle to know which traffic stream has the yield. Vehicles yielding or stopping in the circulating roadways also produces queues and greater accident risks. The presence of frequent rear-end collisions at the yields, especially at the northbound entrance (NJ 47), suggests this is the case. From an operational standpoint, having queues inside the traffic circle can produce gridlock. However, if queuing occurs on the approaches, the circle continues to operate. From a safety perspective, when a rear-end collision occurs inside the circle, gridlock and further collisions are more likely to occur. However, if these collisions are on the approaching roadway, the approach becomes blocked, but traffic continues moving smoothly through the remainder of the traffic circle. Yields should be placed on the approaches.

Placing the yields on the approaches not only reduces the risk of rear-end collisions at conflict points inside the circle but it also ensures that approaching vehicles slow before entering. This reduces overall speeds in the facility and reduces the relative difference in speeds between circulating, entering, and exiting traffic.

Striping

As previously mentioned, Brooklawn Circle does not contain striping within the traffic circle. This creates some confusion as to which lane a driver should use to make a desired movement. In addition, it creates confusion over how many lanes exist in the circle. This leads to sideswipe collisions, particularly at the northbound exit (US 130 North) in the eastern circle.

It is also recommended that the reflectivity of the striping be improved to allow easier visibility during inclement weather and night driving. This type of striping should be placed both in the traffic circle and on the approaches. As an added measure of safety the curb on the inner island should be painted yellow.

Curbing and Barriers

On the eastern circle, it is clear that the westbound approach (US 130 South) is problematic. A large number of vehicles collided with the concrete curb. Drivers enter the traffic circle as if it were a standard intersection, and eventually collide with the curb in the center island. The majority of these accidents took place when it was raining or snowing during evening hours. It is recommended that the entry angle be changed and better lighting be installed. Since the neighboring right-of-way is limited to dramatically change the entry angle of this approach it is recommended that the curbing be cut back approximately ten to twenty feet and replaced with striping. One other possible treatment would be to install "flexi-posts" where the curb is located on the approach. These posts would be approximately at driver eye level. Therefore, the drivers would be likely to see these posts during inclement weather.

Also on the eastern circle, the southbound exit onto NJ 47 is problematic. Just beyond the exit is an intersection with Creek Road. It is possible for vehicles to exit the traffic circle (via NJ 47) and immediately turn left onto Creek Rd. When a queue forms because of this left turn, the queue backs up into the traffic circle. The operation and safety of the circle become jeopardized. It is recommended that a median barrier be introduced to prohibit this move. This barrier would also eliminate the possibility of vehicles turning left onto NJ 47 to enter the circle and also prohibit people from crossing NJ 47 to get to Creek Rd from the gas station immediately across from Creek Road. If this recommendation were placed in the field it would be necessary to either provide an access point to Creek Rd upstream on NJ 47 or provide signage to route people back to Creek Rd.

Driveway Cuts

Within close proximity to the eastern circle are many commercial establishments. Many of these establishments have driveway cuts directly into the circle. When possible these driveway cuts should be removed.

One example is the auto body shop on US 130 just east of the eastern traffic circle. It has multiple driveways. There is one where customers can safely enter the circle and proceed around the circle. There is one further north that is intended to allow access to US 130 north. At this driveway it is possible to “dart” across traffic to get into the circle. Therefore, it is recommended that this driveway be moved to a safer location. This could be done by consolidated it with some of the other local establishments further upstream of the circle.

Also on the eastern circle, there is a gas station between the eastbound entry and the southbound exit (NJ 47). The driveways that are in the circle are the problem spots for this facility. A small curb extension should be added. This extension would allow for an “in” and an “out” driveway. These curb extensions should also be designed not to inhibit trailers from entering the station. Signage should also be added to inform drivers as to what driveway to use.

Empirical Analysis

Supplementing the safety analysis based on the accident histories is an assessment based on the empirical models discussed in the Review of Safety Models chapter that predict accident frequencies.

Average Annual Daily Traffic Estimates

To support the empirical models, Average Annual Daily Traffic volumes (AADTs) were estimated for the traffic circles based on the available morning and evening hourly volumes. Existing and proposed cases were estimated since there is significant rerouting in the alternatives with the introduction of the traffic signal at Old Salem Road/130. Three figures are presented next with the AADTs for each case, with volumes highlighted that change from one case to the next.

As can be seen, volumes in the east circle increase (by approximately 500 to 2,300 vpd or 20 to 96 vph) for all but one section when comparing the existing case with either proposed alternative since the alternatives remove the link from Creek Road into the circle as well as removing the left turns onto Creek Road from NJ47; in other words, Creek Road becomes a right-in, right-out facility at the circle thereby forcing traffic to/from Creek Road to reroute. Likewise, traffic increases on US 130 eastbound leaving the east circle for both alternatives as compared to the existing case (an additional 600 to 900 vpd or 25 to 38 vph).

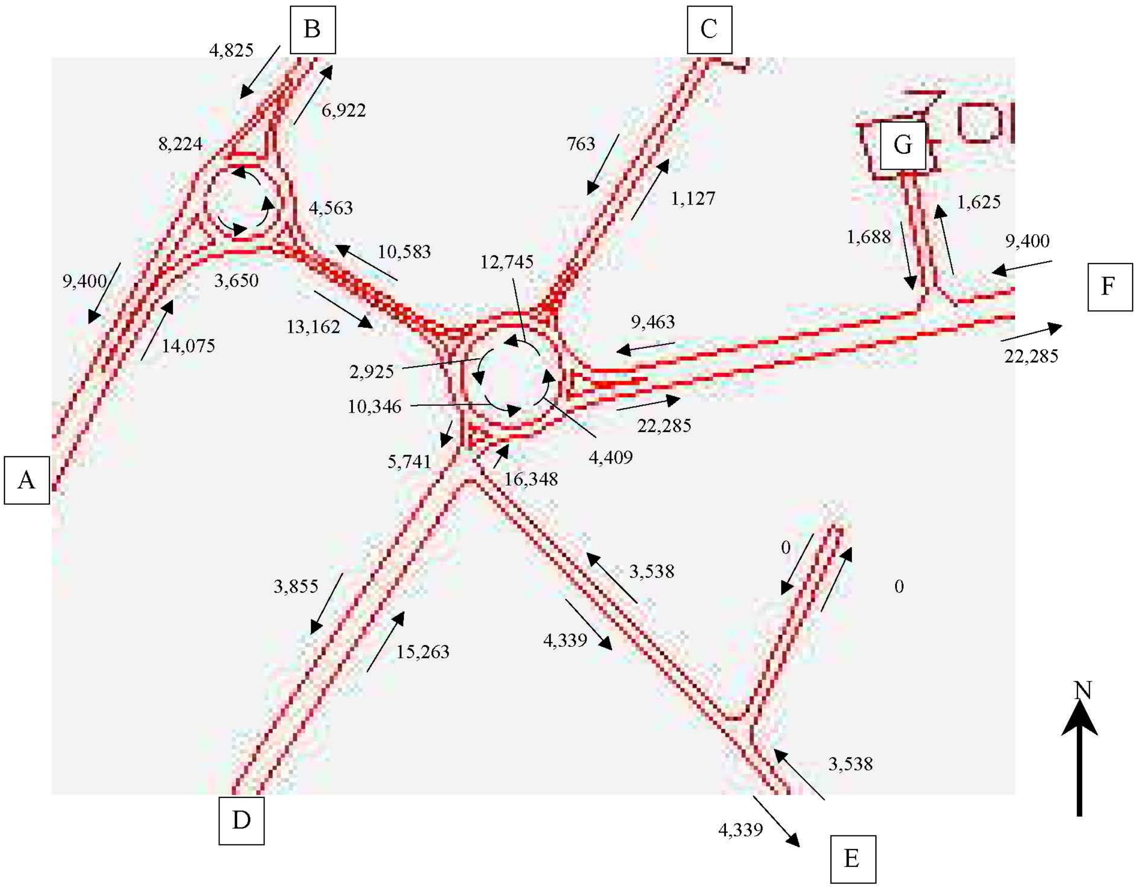


Figure 27. Estimated AADTs for existing conditions

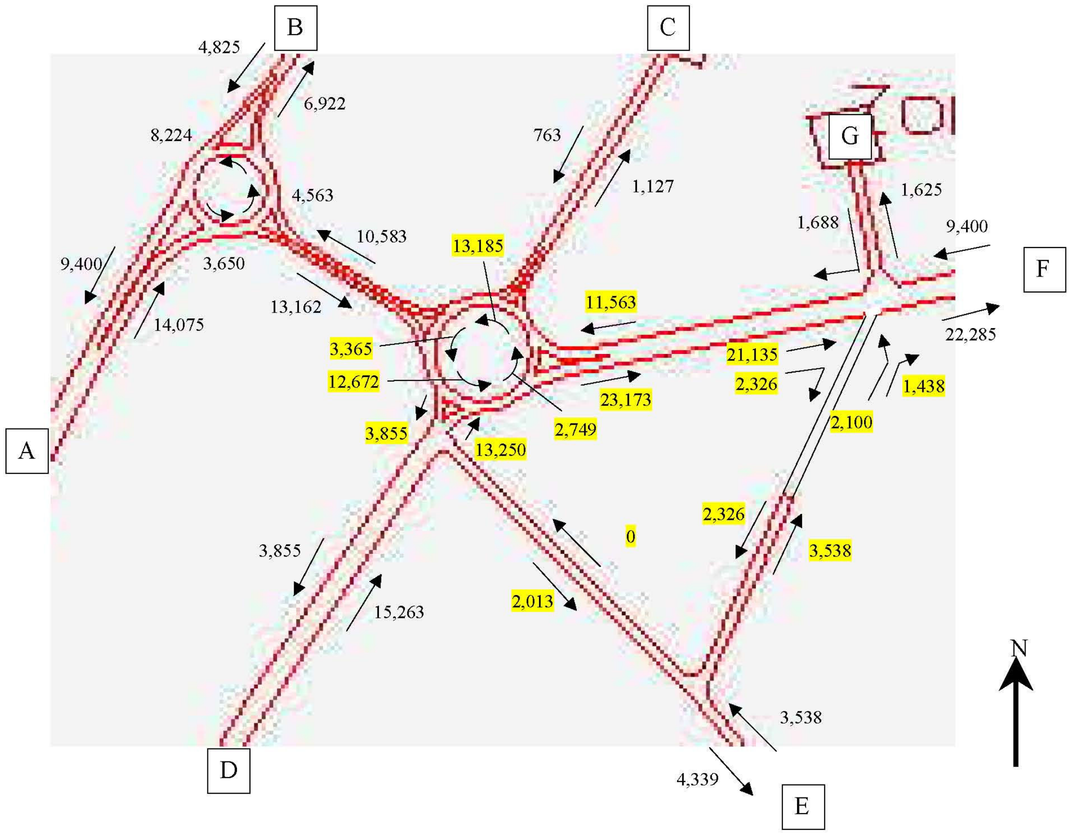


Figure 28. Estimated AADTs for Alternative 2B

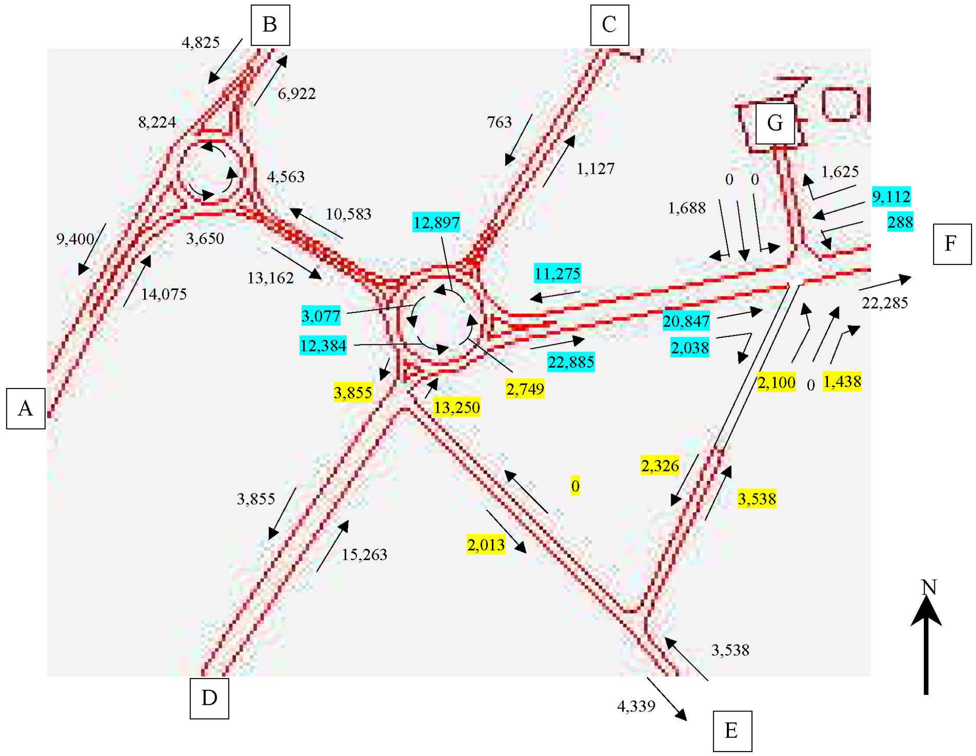


Figure 29. Estimated AADTs for Alternative 2D

<u>Maycock & Hall (1984)</u> **[1]**

As can be deduced by reviewing the description of Maycock and Hall's model (see Maycock & Hall – UK Model (1984)[1], page 19), predictions of the accident frequencies are dependent upon a number of inputs: the entry (Q_e), conflicting (Q_c), and exiting (Q_{ex}) flows, expressed as AADTs; the curvature (C_e) of the entry (reciprocal of the radius), the entry width (e), the approach width (v), the approach curvature category (C_a), the ratio of the inscribed diameter to the diameter of the central island (R), the percentage of motorcycles in the approach traffic stream (P_a), the angle to the next downstream entry (θ), the gradient category (g), and the sight distance on the approach (V_r). The values of these parameters for each of the approaches in the existing conditions are shown in the table below. The AADTs are in thousands. The angle is expressed in degrees. The sight distances are set to 500 m indicating that they are effectively infinite.

It should be noted that the Maycock & Hall model cannot take into account the variations tested for each of Alternative 2B and Alternative 2D since these changes would not be reflected by the model's variables.

Table 15. Input values for all cases

Case		Q_e	Q_c	Q_{ex}	C_e**	e*	v	C_a	R	P_m	Θ	g	V_r
CASE 1 Existing Condition	**EAST CIRCLE**												
	US 130 SWB	9.463	4.41	22.30	0.030	9.5	10.0	-1	1.43	5	48	0	500
	NJ 47 NB	16.348	10.30	5.74	0.020	13.1	8.2	0	1.43	5	132	0	500
	US 130 EB	13.162	2.93	10.60	0.030	7.6	7.2	0	1.43	5	89	0	500
	Hannevig Ave SB	0.763	12.70	1.13	0.040	5.8	6.2	0	1.43	5	91	0	500
	WEST CIRCLE												
	US 130 NB	14.08	3.65	9.40	0.016	10.1	8.6	0	1.51	5	90	0	500
	New Broadway Ave SB	4.83	8.22	6.92	0.000	9.0	4.0	-1	1.51	5	90	0	500
	US 130 WB	10.58	4.56	13.16	0.023	9.7	7.2	0	1.51	5	180	0	500
CASE 2 Alternative 2B	**EAST CIRCLE**												
	US 130 SWB	11.563	2.75	23.17	0.030	9.5	10.0	-1	1.43	5	48	0	500
	NJ 47 NB	13.250	12.70	3.86	0.020	13.1	8.2	0	1.43	5	132	0	500
	US 130 EB	13.162	3.37	10.58	0.030	7.6	7.2	0	1.43	5	89	0	500
	Hannevig Ave SB	0.763	13.20	1.13	0.040	5.8	6.2	0	1.43	5	91	0	500
	WEST CIRCLE												
	US 130 NB	14.08	3.65	9.40	0.016	10.1	8.6	0	1.51	5	90	0	500
	New Broadway Ave SB	4.83	8.22	6.92	0.000	9.0	4.0	-1	1.51	5	90	0	500
	US 130 WB	10.58	4.56	13.16	0.023	9.7	7.2	0	1.51	5	180	0	500
CASE 3 Alternative 2D	**EAST CIRCLE**												
	US 130 SWB	11.275	2.75	22.89	0.03	9.5	10.0	-1	1.43	5	48	0	500
	NJ 47 NB	13.250	12.40	3.86	0.02	13.1	8.2	0	1.43	5	132	0	500
	US 130 EB	13.162	3.08	10.58	0.03	7.6	7.2	0	1.43	5	89	0	500
	Hannevig Ave SB	0.763	12.90	1.13	0.04	5.8	6.2	0	1.43	5	91	0	500
	WEST CIRCLE												
	US 130 NB	14.08	3.65	9.40	0.016	10.1	8.6	0	1.51	5	90	0	500
	New Broadway Ave SB	4.83	8.22	6.92	0.000	9.0	4.0	-1	1.51	5	90	0	500
	US 130 WB	10.58	4.56	13.16	0.023	9.7	7.2	0	1.51	5	180	0	500

* = "e" for the East Circle is measured off of drawings at a scale of 100'=2.62", then converted to meters (divide by 3.281); "e" for the West Circle is measured off of globeXplorer.com orthophotos of the site matching the East Circle departure with the West Circle approach.

** = "Ce" = 1/Re, Re is the min entry radius for a through movement, measured with keyhole.com orthophotos for the East Circle and from drawings for the West Circle.

Table 16 presents a comparison of the accident rates predicted by Maycock and

Hall (1984) for the existing and enhanced conditions. It should not be expected that the accident rates would match the observed performance of the traffic circle. The equations are calibrated for British conditions, not American; and they are for four-leg, single lane roundabouts; not multi-lane traffic circles. That having been said, examining the predictions is still valuable, especially the changes in those predictions based on the geometric enhancements proposed.

Table 16. Estimated accident rates based on Maycock & Hall

		ACCIDENT RATE			% CHANGE	
EAST CIRCLE	**Location**	**Existing**	**Alt 2B**	**Alt 2D**	**1→2**	**1→4**
Entering/Circ	US 130 SWB	0.183	0.176	0.173	3.9%	5.5%
	NJ 47 NB	0.408	0.383	0.380	6.2%	6.9%
	US 130 EB	0.172	0.181	0.175	-5.2%	-1.8%
	Hannevig Ave SB	0.026	0.026	0.026	-1.2%	-0.4%
Approach-RearEnd	US 130 SWB	0.320	0.456	0.436	-42.3%	-36.1%
	NJ 47 NB	0.502	0.347	0.347	30.9%	30.9%
	US 130 EB	0.639	0.639	0.639	0.0%	0.0%
	Hannevig Ave SB	0.006	0.006	0.006	0.0%	0.0%
Single Vehicle	US 130 SWB	1.015	1.196	1.172	-17.9%	-15.4%
	NJ 47 NB	0.749	0.631	0.631	15.8%	15.8%
	US 130 EB	0.567	0.567	0.567	0.0%	0.0%
	Hannevig Ave SB	0.057	0.057	0.057	0.0%	0.0%
Other	US 130 SWB	0.147	0.121	0.118	18.0%	19.5%
	NJ 47 NB	0.409	0.407	0.400	0.5%	2.2%
	US 130 EB	0.139	0.154	0.144	-10.8%	-3.8%
	Hannevig Ave SB	0.051	0.052	0.051	-2.5%	-0.9%
WEST CIRCLE	**Location**	**Existing**	**Alt 2B**	**Alt 2D**		
Entering/Circ	US 130 NB	0.330	0.330	0.330	0.0%	0.0%
	New Broadway Ave SB	0.559	0.559	0.559	0.0%	0.0%
	US 130 WB	0.118	0.118	0.118	0.0%	0.0%
Approach-RearEnd	US 130 NB	0.470	0.470	0.470	0.0%	0.0%
	New Broadway Ave SB	0.057	0.057	0.057	0.0%	0.0%
	US 130 WB	0.346	0.346	0.346	0.0%	0.0%
Single Vehicle	US 130 NB	0.660	0.660	0.660	0.0%	0.0%
	New Broadway Ave SB	0.084	0.084	0.084	0.0%	0.0%
	US 130 WB	0.455	0.455	0.455	0.0%	0.0%
Other	US 130 NB	0.171	0.171	0.171	0.0%	0.0%
	New Broadway Ave SB	0.142	0.142	0.142	0.0%	0.0%
	US 130 WB	0.164	0.164	0.164	0.0%	0.0%

** Existing and all alternatives based on AADTs generated from the OD Tables.
0.xxx = lower (better) accident rates predicted
0.xxx = higher (worse) accident rates predicted

Similar to the Collingwood Traffic Circle results, as entering/circulating accidents are predicted to decrease, then approach-rear end accidents are predicted to slightly increase.

The entry-circulating accident rates are predicted to decrease substantially, principally because of the major changes in geometry. The approach accident rates mostly increase, for the same reason that the entry-circulating rates decreased, because of the change in geometry. If the curvature of the 33 EBD / 34 SBD approach was not quite so sharp, the entry-circulating accident rate prediction would increase, but the approach accident rate prediction would decrease. (That's a minor modification that NJDOT might want to consider.) The single vehicle accident rates increase because of the greater curvature on the approaches. For all but the 33 EBD / 34 SBD approach, those increases are small. The increase for that approach could be mitigated if the radius on that approach was increased.

***Arndt (1998)*[(10)]**

Arndt's (1998) model is very different from Maycock and Hall (1984). It is predicated on different data (specifically, speeds are included) and structured in an alternate manner. The accident rate predictions are not likely to be the same. It has not been calibrated for American conditions and it is intended to be used for roundabouts, not traffic circles. However, it should be a reasonable tool for comparing alternatives.

The variable labels are as follows. A_* denotes an accident rate prediction; Q_a is the approach volume (as an AADT); N_c is the number of circulating lanes; $S(Q_{ci})$ is shorthand for the conflicting volume at a given approach; S_{ra} is the average relative difference in 85^{th} percentile speeds between the approach and the circulating traffic; t_{Ga} is the average time to get from the yield line to the conflict point; S_{ri} and t_{Gi} are identical thoughts for specific approaches; d_{Gi} is the distance in meters from the yield line to the conflict point; N_a is the number of lanes on the approach; L is the length in meters of the horizontal segment for which the single vehicle accident rate is being predicted; S is the 85th percentile speed at the beginning of that segment; ΔS is the change in 85th percentile speed occurring across the segment; and R is the radius in meters of the segment.

The empirical model inputs and calculated variables for the existing conditions and all alternatives are shown in Table 17.

As can be seen, the volumes for Cases 2 and 3 are the same as are the volumes for Cases 4 and 5. What changes between these two pairs of alternatives are the speeds through the facility. The speeds shown for the proposed alternatives are from the PARAMICS simulations whereas the existing speeds are based on the facility speed limits currently in force. A drawback of the Arndt models realized during this analysis is that accident rates for certain movements are undefined (designated "ud" in Table 18) because the circulating speed (S_{ci}) is greater than the approach speed (S_a), leading to a negative value for the relative difference in speeds (S_{ri}). This drawback affects both the entering/circulating and exiting/circulating accident rates.

For all of the alternatives several variables (such as the number of lanes and radii) stay constant throughout, as is evident in Table 17. Hence, we can see the impact of operational changes including speed reductions, relocation of yield signs, and upstream signal designs. To view the impacts, Table 18 presents the accident rates and percentage change as compared to the existing case for the five cases under consideration.

For the most part, safety conditions were found to improve under all proposed alternatives. The exceptions include particular accident types on single approaches. For example, sideswipe accidents are anticipated to increase slightly (increase by 11 percent) in all cases for two approaches, US 130 EB and

Hannevig Avenue. Hence, the results from Maycock & Hall are augmented with this new information that sideswipe accident prevention may need further work prior to the final design. The other example for all proposed cases is the “other accident” rate for US 130 SWB which worsens approximately 20 percent; this result substantiates that found via the Maycock & Hall method.

Table 17. Arndt model inputs and calculated variables

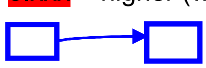
			INPUT													CALCULATED	
		Approach Location	Q_a (or Q)	$S(Q_{ci})$	$S(Q_{ei})$	S_a	S_{ci}	S	ΔS	N_a	N_c	d_{Gi}	L	R	Δfl	S_{ra} (or S_{ri})	t_{Ga} (or t_{Gi})
CASE 1 EXISTING	East	US 130 SWB	9.463	4.409	22.285	80	30	80	40	2	2	10	10	35	0.5	50	1.200
		NJ 47 NB	16.348	10.346	5.741	44	5	44	22	2	2	10	10	50	0.5	39	7.200
		US 130 EB	13.162	2.925	10.583	80	30	80	40	1	2	10	10	40	0.5	50	1.200
		Hannevig Ave SB	0.763	12.745	1.127	32	32	32	16	1	2	10	10	28	0.5	0	1.125
	West	US 130 NB	14.075	3.650	9.399	80	10	80	40	2	2	10	10	63	0.5	70	3.600
		New Broadway Ave SB	4.825	8.224	6.922	40	36	40	20	1	2	10	10	500	0.5	4	1.000
		US 130 WB	10.583	4.563	13.162	80	22	80	40	1	2	10	10	43	0.5	58	1.636
CASE 2 ALT. 2B	East	US 130 SWB	11.563	2.749	23.173	36	23	36	18	2	2	10	10	35	0.5	13	1.585
		NJ 47 NB	13.250	12.672	3.855	36	28	36	18	2	2	10	10	50	0.5	8	1.271
		US 130 EB	13.162	3.365	10.583	18	31	18	9	1	2	10	10	40	0.5	-13	1.172
		Hannevig Ave SB	0.763	13.185	1.127	32	32	32	16	1	2	10	10	28	0.5	0	1.125
	West	US 130 NB	14.075	3.650	9.399	36	18	36	18	2	2	10	10	63	0.5	17	1.974
		New Broadway Ave SB	4.825	8.224	6.922	25	36	25	12	1	2	10	10	500	0.5	-11	1.009
		US 130 WB	10.583	4.563	13.162	36	22	36	18	1	2	10	10	43	0.5	13	1.630
CASE 3 ALT. 2B W/ ENH.	East	US 130 SWB	11.563	2.749	23.173	28	24	28	14	2	2	10	10	35	0.5	4	1.520
		NJ 47 NB	13.250	12.672	3.855	27	29	27	14	2	2	10	10	50	0.5	-1	1.261
		US 130 EB	13.162	3.365	10.583	18	36	18	9	1	2	10	10	40	0.5	-18	1.004
		Hannevig Ave SB	0.763	13.185	1.127	27	27	27	14	1	2	10	10	28	0.5	0	1.333
	West	US 130 NB	14.075	3.650	9.399	35	18	35	17	2	2	10	10	63	0.5	17	1.991
		New Broadway Ave SB	4.825	8.224	6.922	24	36	24	12	1	2	10	10	500	0.5	-12	1.004
		US 130 WB	10.583	4.563	13.162	27	21	27	14	1	2	10	10	43	0.5	6	1.724
CASE 4 ALT. 2D	East	US 130 SWB	11.275	2.749	22.885	35	24	35	17	2	2	10	10	35	0.5	10	1.480
		NJ 47 NB	13.250	12.384	3.855	35	28	35	17	2	2	10	10	50	0.5	6	1.264
		US 130 EB	13.162	3.077	10.583	18	36	18	9	1	2	10	10	40	0.5	-17	1.004
		Hannevig Ave SB	0.763	12.897	1.127	32	32	32	16	1	2	10	10	28	0.5	0	1.125
	West	US 130 NB	14.075	3.650	9.399	36	19	36	18	2	2	10	10	63	0.5	17	1.899
		New Broadway Ave SB	4.825	8.224	6.922	25	36	25	13	1	2	10	10	500	0.5	-11	1.007
		US 130 WB	10.583	4.563	13.162	34	21	34	17	1	2	10	10	43	0.5	13	1.718
CASE 5 ALT. 2D W/ APP YIELDS	East	US 130 SWB	11.275	2.749	22.885	5	32	5	3	2	2	10	10	35	0.5	-26	1.136
		NJ 47 NB	13.250	12.384	3.855	36	36	36	18	2	2	10	10	50	0.5	0	0.993
		US 130 EB	13.162	3.077	10.583	19	36	19	10	1	2	10	10	40	0.5	-17	0.998
		Hannevig Ave SB	0.763	12.897	1.127	27	27	27	14	1	2	10	10	28	0.5	0	1.333
	West	US 130 NB	14.075	3.650	9.399	25	34	25	13	2	2	10	10	63	0.5	-9	1.044
		New Broadway Ave SB	4.825	8.224	6.922	26	36	26	13	1	2	10	10	500	0.5	-10	0.989
		US 130 WB	10.583	4.563	13.162	5	34	5	2	1	2	10	10	43	0.5	-29	1.049

x.xxx = input values that change from one alternative to the next

xx = circulating speed is higher than approach speed (S_{ci}>S_a) so S_{ri}<0. This leads to the enter/circulating and exiting/circulating (A_e and A_d) accident rates being undefined at this location.

Table 18. Estimated accident rates based on Arndt equations

	Approach Location	Accident Rates Case 1 Existing	Case 2 Alt 2B	Case 3 Alt 2B w/Enh	Case 4 Alt 2D	Case 5 Alt 2D w/Yields	Percent Change 1 → 2	1 → 3	1 → 4	1 → 5
	Entering/Circulating									
East	US 130 SWB	0.669	0.093	0.019	0.066	ud	86%	97%	90%	ud
East	NJ 47 NB	0.598	ud	0.006	0.071	ud	84%	ud	88%	ud
East	US 130 EB	0.661	ud	ud	ud	ud	ud	ud	ud	ud
East	Hannevig Ave SB	0.000	0.000	0.000	0.000	0.000	0%	0%	0%	0%
West	US 130 NB	0.943	0.156	0.147	0.148	ud	83%	84%	84%	ud
West	New Broadway Ave SB	0.020	ud	ud	ud	ud	ud	ud	ud	ud
West	US 130 WB	0.823	0.109	0.038	0.099	ud	87%	95%	88%	ud
	Approach/Rear-end									
East	US 130 SWB	0.844	0.018	0.005	0.015	0.000	98%	99%	98%	100%
East	NJ 47 NB	0.181	0.061	0.016	0.051	0.059	66%	91%	72%	67%
East	US 130 EB	0.206	0.000	0.000	0.000	0.000	100%	100%	100%	100%
East	Hannevig Ave SB	0.000	0.000	0.000	0.000	0.000	-2%	55%	-1%	55%
West	US 130 NB	1.296	0.027	0.024	0.027	0.005	98%	98%	98%	100%
West	New Broadway Ave SB	0.004	0.000	0.000	0.000	0.000	90%	91%	89%	87%
West	US 130 WB	0.203	0.004	0.001	0.003	0.000	98%	99%	98%	100%
	Single Vehicle									
East	US 130 SWB	0.305	0.014	0.005	0.012	0.000	95%	98%	96%	100%
East	NJ 47 NB	0.025	0.009	0.003	0.008	0.009	65%	89%	70%	65%
East	US 130 EB	0.347	0.001	0.001	0.001	0.001	100%	100%	100%	100%
East	Hannevig Ave SB	0.001	0.001	0.000	0.001	0.000	0%	50%	0%	50%
West	US 130 NB	0.158	0.006	0.005	0.006	0.001	96%	97%	96%	99%
West	New Broadway Ave SB	0.000	0.000	0.000	0.000	0.000	86%	88%	85%	82%
West	US 130 WB	0.234	0.008	0.003	0.007	0.000	96%	99%	97%	100%
	Exiting/Circulating									
East	US 130 SWB	1.834	0.007	0.000	0.003	ud	100%	100%	100%	ud
East	NJ 47 NB	0.343	ud	0.000	0.000	ud	100%	ud	100%	ud
East	US 130 EB	0.969	ud	ud	ud	ud	ud	ud	ud	ud
East	Hannevig Ave SB	0.000	0.000	0.000	0.000	0.000	0%	0%	0%	0%
West	US 130 NB	3.852	0.012	0.010	0.010	ud	100%	100%	100%	ud
West	New Broadway Ave SB	0.000	ud	ud	ud	ud	ud	ud	ud	ud
West	US 130 WB	2.393	0.006	0.000	0.004	ud	100%	100%	100%	ud
	Sideswipe									
East	US 130 SWB	0.013	0.011	0.011	0.011	0.011	18%	18%	19%	19%
East	NJ 47 NB	0.036	0.036	0.036	0.035	0.035	1%	1%	2%	2%
East	US 130 EB	0.012	0.014	0.014	0.013	0.013	-11%	-11%	-4%	-4%
East	Hannevig Ave SB	0.005	0.005	0.005	0.005	0.005	-2%	-2%	-1%	-1%
West	US 130 NB	0.015	0.015	0.015	0.015	0.015	0%	0%	0%	0%
West	New Broadway Ave SB	0.013	0.013	0.013	0.013	0.013	0%	0%	0%	0%
West	US 130 WB	0.015	0.015	0.015	0.015	0.015	0%	0%	0%	0%
	Other									
East	US 130 SWB	0.041	0.050	0.050	0.048	0.048	-22%	-22%	-19%	-19%
East	NJ 47 NB	0.070	0.057	0.057	0.057	0.057	19%	19%	19%	19%
East	US 130 EB	0.056	0.056	0.056	0.056	0.056	0%	0%	0%	0%
East	Hannevig Ave SB	0.003	0.003	0.003	0.003	0.003	0%	0%	0%	0%
West	US 130 NB	0.060	0.060	0.060	0.060	0.060	0%	0%	0%	0%
West	New Broadway Ave SB	0.021	0.021	0.021	0.021	0.021	0%	0%	0%	0%
West	US 130 WB	0.045	0.045	0.045	0.045	0.045	0%	0%	0%	0%

* Existing and all alternatives based on AADTs generated from the OD Tables.
ud = undefined
0.xxx = higher (worse) accident rates predicted, negative percent change

= corresponding approaches between alternatives

Further comparing the two methods across accident types (see Table 19), it can be seen that Case 5 (Alternative 2D with Approach Yields) is overall the best option. Case 4 is the best according to Maycock and Hall and then using the Arndt model for distinguishing between the two operational conditions of Cases 4 and 5 where yield control is moved from its existing locations to only the approaches, it is found that Case 5 is the safest proposal overall.

Table 19. Percent difference in accident rates between alternatives

	MODEL USED / CASES COMPARED					
	Maycock & Hall		**Arndt**			
ACCIDENT TYPE	1→2	1→4	1→2	1→3	1→4	1→5
Entering/Circulating	1.3%	2.0%	*85.1%	*91.6%	*86.7%	*0%
Approach-Rear-End	0.8%	1.7%	95.9%	98.3%	96.4%	97.6%
Single Vehicle	-1.7%	-1.1%	96.4%	98.4%	96.7%	98.9%
Other	1.0%	2.6%	1.4%	1.4%	1.9%	1.9%
Exiting/Circulating	n/a	n/a	*99.7%	*99.9%	*99.8%	*100.0%
Sideswipe	n/a	n/a	1.0%	1.0%	2.6%	2.6%
Total Percent Change	**-0.1%**	**0.8%**	*93.4%	*95.4%	*93.9%	*88.7%

0.xxx = higher (worse) accident rates predicted, negative percent change
0.xxx = best improvement among alternatives
* These percent changes are adjusted from the raw percent changes to account for the undefined accident rates shown in the previous table.

Modeling the Treatments for Simulation

The safety treatment options discussed above are easily modeled using the PARAMICS computer software package. However, care is needed. PARAMICS has limitations in modeling the effects of certain geometric parameters. For example, the roadway width may be altered or superelevation imposed on the circulating roadway in the traffic circle. In the real world environment, these treatments would both have a significant impact on speeds in the facility. However, PARAMICS does not respond to these changes in geometry. What PARAMICS does allow the user to do is input a given percent speed reduction that would be anticipated due to the presence of a curve. Therefore, when modeling the treatments above, a percent speed reduction must be entered to reflect the impacts of making such a change.

The existing conditions and four improvement scenarios were developed for the circles at Brooklawn. The scenarios that were developed are:

- “Case 1” – Existing Conditions,
- “Case 2” – Alternate 2B in the Delaware Valley Regional Planning Commission (DVRPC) *US 130 Brooklawn Circles Concept Development Report* (February 2002),
- “Case 3” – Case 2 in addition to site specific enhancements such as geometry, lighting and signage,
- “Case 4” – Alternative 2D in the DVRPC Report with the same enhancements as Case 3, and
- “Case 5” – Case 4 with yield controls on each of the approaches.

Case 2 can be seen in Figure 30. In this alternative, left turns are prohibited from NJ 47 southbound onto Creek Road by a median barrier. Right turns from Creek Road into the circle are also eliminated. Right turns from NJ 47 NB onto Creek Road are still permitted. Old Salem Road is altered to compensate for these changes. At the intersection of Old Salem Road and US 130 a traffic light would be installed. This light would permit vehicles from Creek Road to access US 130 northbound and southbound. US 130 northbound traffic could turn right onto Old Salem Road. However, US 130 southbound traffic could only proceed straight.

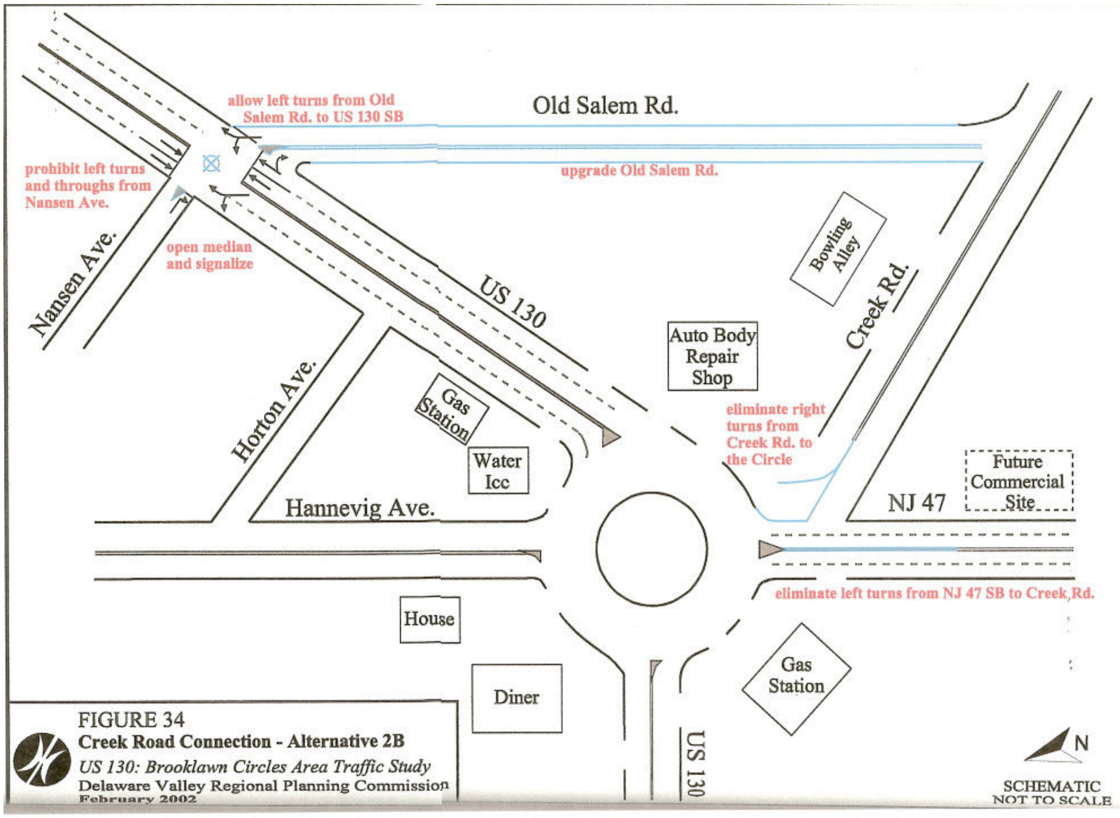


Figure 30. Case 2 – DRRPC Alternative 2B

Source: DVRPC *US 130 Brooklawn Circles Concept Development Report* (February 2002)[32]

Case 3 aims to reduce vehicle speeds on the approaches and within the circulating roadway by introducing safety enhancements such as geometry and lighting.

Case 4 can be seen in Figure 31. This alternative builds on Case 2 (Alternative 2B). It allows left turns from US 130 South onto Old Salem Road. This scenario removes unnecessary U-turn movements through the circle for vehicles traveling from the north going to Creek Road. This alternative also includes the enhancements that were provided for the previous scenario.

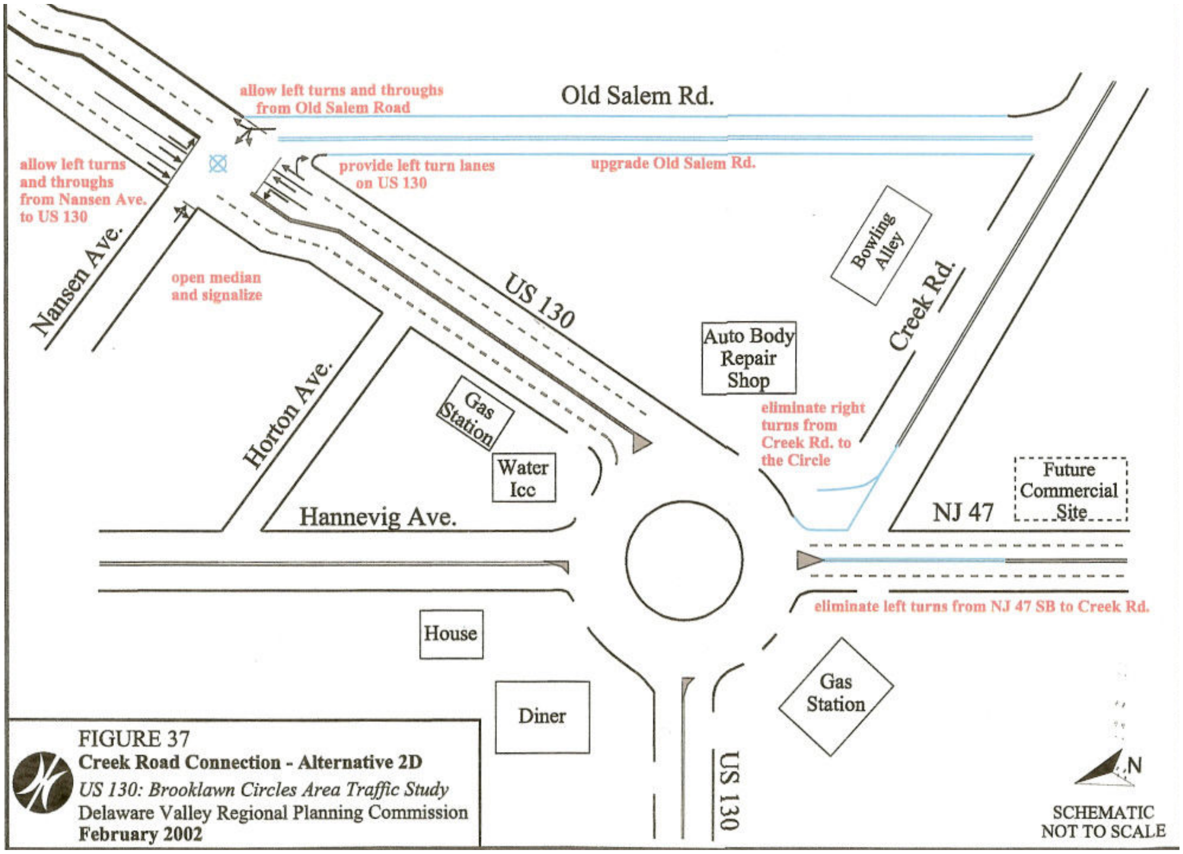


Figure 31. Case 4 – DVRPC Alternative 2D

Source: DVRPC *US 130 Brooklawn Circles Concept Development Report* (February 2002) [32]

Case 5 builds on Case 4 by placing yield controls on each of the approaches.

Each of the cases has been modeled in PARAMICS and analyzed using two output metrics: speed distributions at specific locations and speed trajectories. Speed distributions measure the smoothness of the merges by looking at the differences between circulating and entering vehicles at the conflict points. Ideally, for the vehicles that pass the conflict point unimpeded, one would like to see a small difference in speeds, indicating that the free-flow entering and circulating speeds are approximately equal. Unsafe conflict points occur when there are large differences in these free-flow speeds. Speed trajectories indicate how vehicle speeds change as the traffic circle is traversed. Ideally, one would like to see a gradual decrease in speed as the vehicle approaches the facility, a constant speed through the facility, and a gradual increase in speed as the vehicle exits the facility. When large increases or decreases in speed occur, this indicates that queuing may be occurring or that vehicles may be traveling unsafely.

Modeling the Treatments for Simulation

The safety treatment options discussed above are easily modeled using the PARAMICS computer software package. However, care is needed. PARAMICS has limitations in modeling the effects of certain geometric parameters. For example, the roadway width may be altered or superelevation imposed on the circulating roadway in the traffic circle. In the real world environment, these treatments would both have a significant impact on speeds in the facility. However, PARAMICS does not respond to these changes in geometry. What PARAMICS does allow the user to do is input a given percent speed reduction that would be anticipated due to the presence of a curve. Therefore, when modeling the treatments above, a percent speed reduction must be entered to reflect the impacts of making such a change.

The existing conditions and four improvement scenarios were developed for the circles at Brooklawn. The scenarios that were developed are:

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Case 2 can be seen in Figure 30. In this alternative, left turns are prohibited from

NJ 47 southbound onto Creek Road by a median barrier. Right turns from Creek Road into the circle are also eliminated. Right turns from NJ 47 NB onto Creek Road are still permitted. Old Salem Road is altered to compensate for these changes. At the intersection of Old Salem Road and US 130 a traffic light would be installed. This light would permit vehicles from Creek Road to access US 130 northbound and southbound. US 130 northbound traffic could turn right onto Old Salem Road. However, US 130 southbound traffic could only proceed straight.

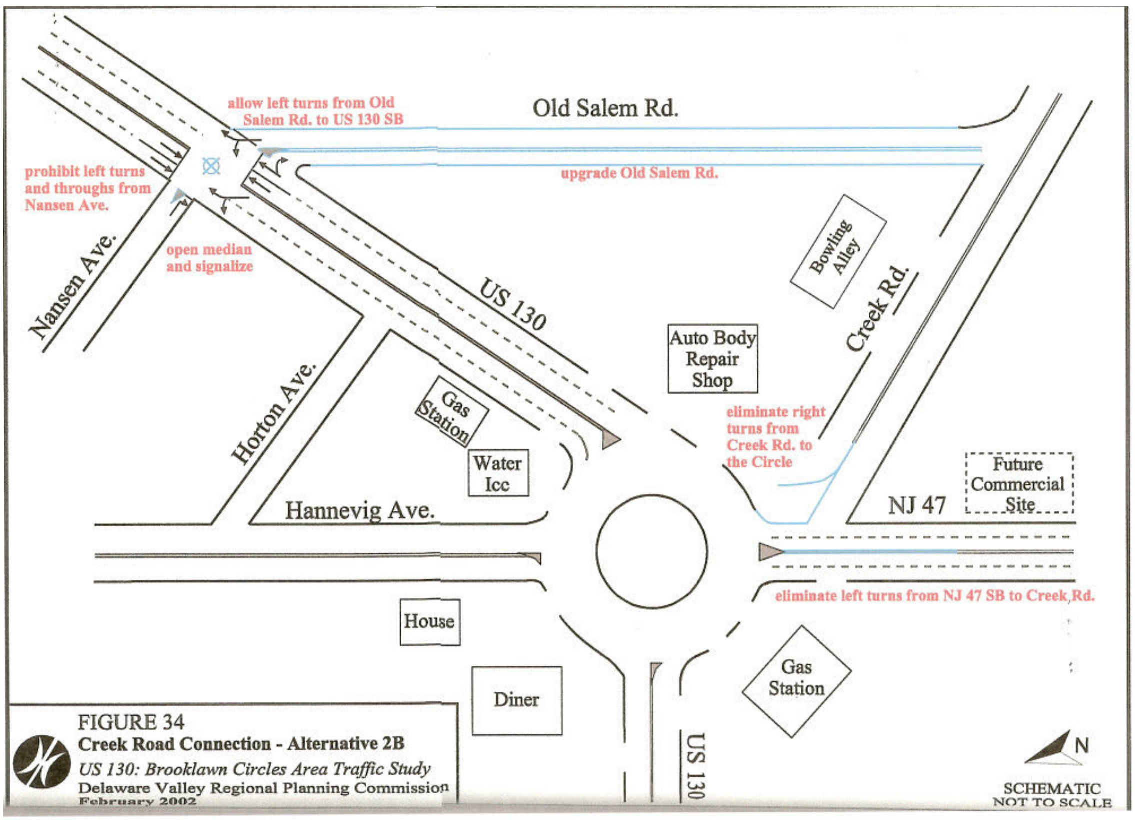


Figure 32. Case 2 – DRRPC Alternative 2B

Source: DVRPC *US 130 Brooklawn Circles Concept Development Report* (February 2002)[32]

Case 3 aims to reduce vehicle speeds on the approaches and within the circulating roadway by introducing safety enhancements such as geometry and lighting.

Case 4 can be seen in Figure 31. This alternative builds on Case 2 (Alternative 2B). It allows left turns from US 130 South onto Old Salem Road. This scenario removes unnecessary U-turn movements through the circle for vehicles traveling from the north going to Creek Road. This alternative also includes the enhancements that were provided for the previous scenario.

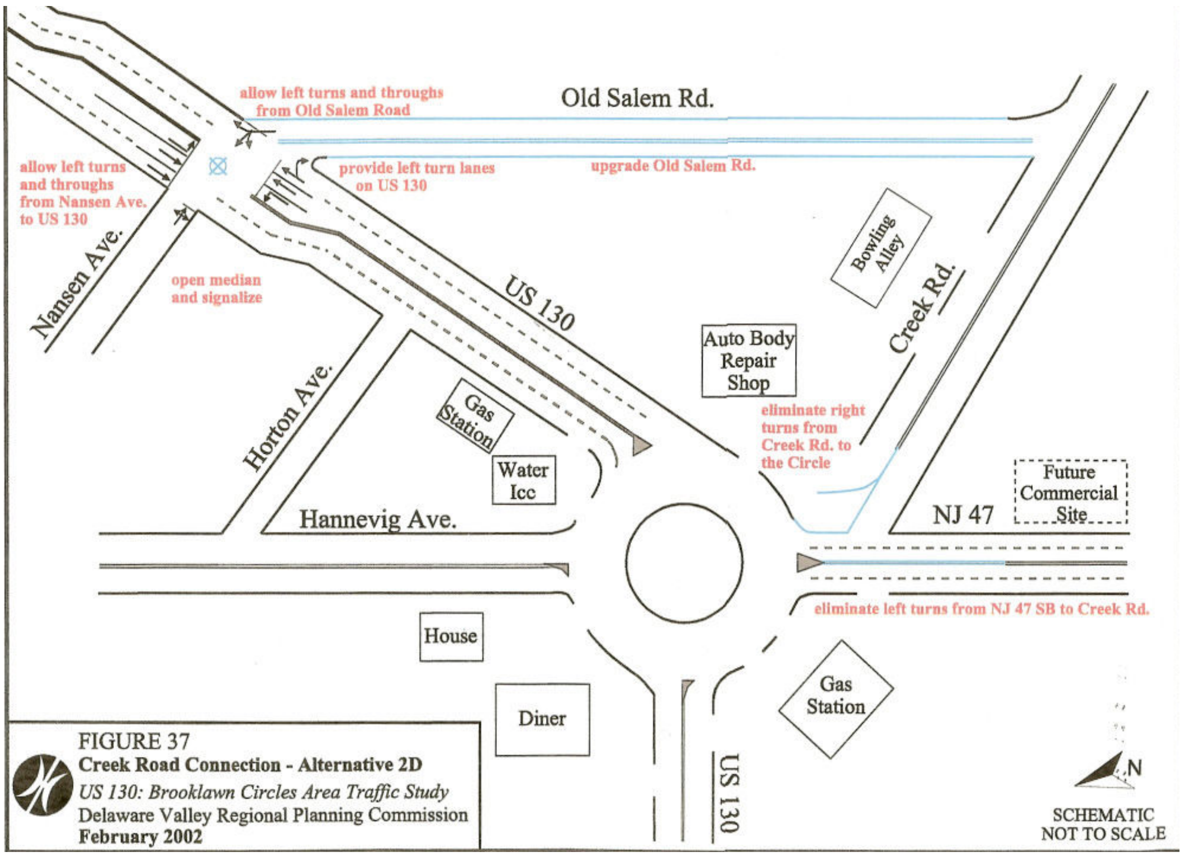


Figure 33. Case 4 – DVRPC Alternative 2D

Source: DVRPC *US 130 Brooklawn Circles Concept Development Report* (February 2002) [32]

Case 5 builds on Case 4 by placing yield controls on each of the approaches.

Each of the cases has been modeled in PARAMICS and analyzed using two output metrics: speed distributions at specific locations and speed trajectories.

Speed distributions measure the smoothness of the merges by looking at the differences between circulating and entering vehicles at the conflict points. Ideally, for the vehicles that pass the conflict point unimpeded, one would like to see a small difference in speeds, indicating that the free-flow entering and circulating speeds are approximately equal. Unsafe conflict points occur when there are large differences in these free-flow speeds. Speed trajectories indicate how vehicle speeds change as the traffic circle is traversed. Ideally, one would like to see a gradual decrease in speed as the vehicle approaches the facility, a constant speed through the facility, and a gradual increase in speed as the vehicle exits the facility. When large increases or decreases in speed occur, this indicates that queuing may be occurring or that vehicles may be traveling unsafely.

Eastern Circle, Westbound Approach (Route 130 SB)

The main location where accidents occur is at the Route 130 Southbound approach to the east circle.

In Case 1 (existing conditions) the simulation suggests there are substantial differences in the free-flow speeds on the approach and circulating roadway as seen in Figure 34. This is problematic for several reasons. First, the yield is on the circulating roadway, so the approaching vehicles do not tend to slow down.

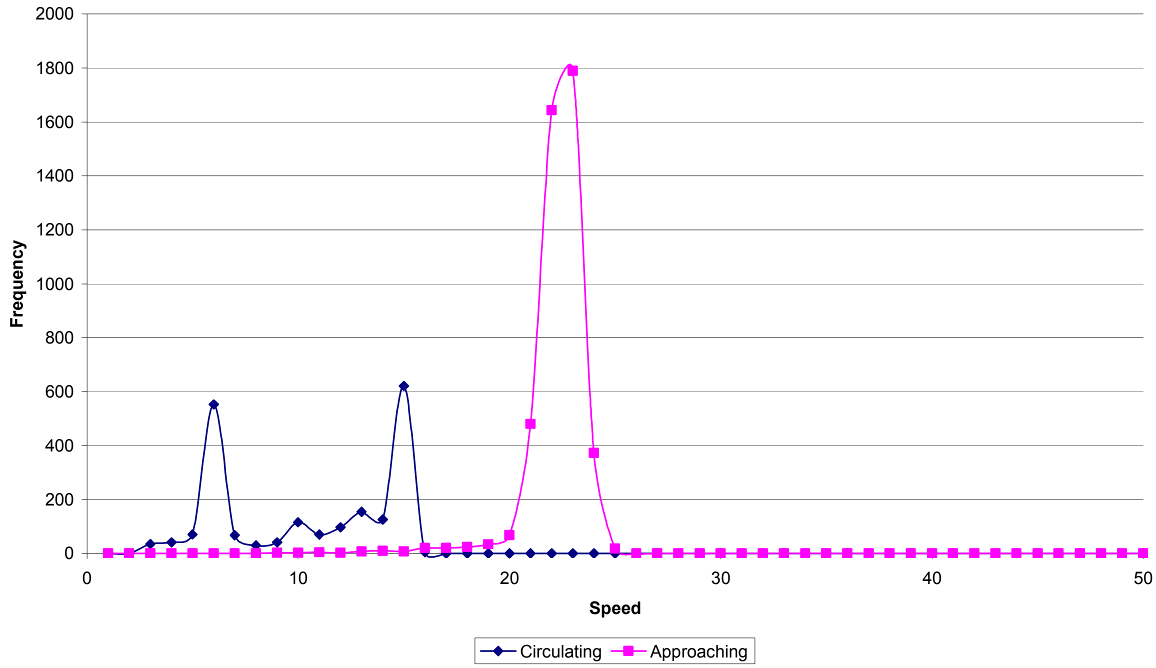


Figure 34. Rt. 130 SB speed distributions – Case 1

This does not promote uniform speeds throughout the circle and helps to cause problems at other locations. Ideally, at this location the approaching and circulating free-flow speeds would be the same.

Case 2 produces little change in this situation. This is because no approach specific plans are taken into account.

Case 3 provides better signage and lighting on this approach as well as minor geometric changes to reduce the approaching speeds. Figure 35 shows that for this case both the circulating and approaching speeds similar with the exception of the small circulating peak near 5 MPH. This similarity between speeds will greatly reduce the number of incidents at this location.

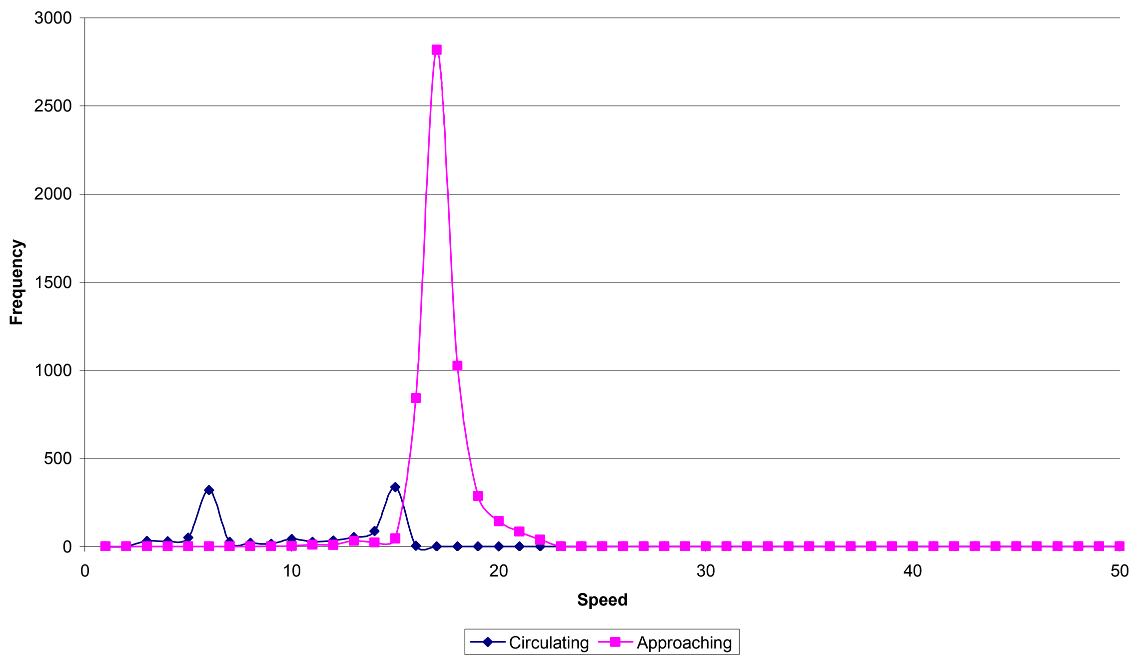


Figure 35. Rt. 130 SB speed distributions – Case 3

In Case 5, by moving the yield control to the approach, the results are substantially different. Figure 36 shows the results of this case.

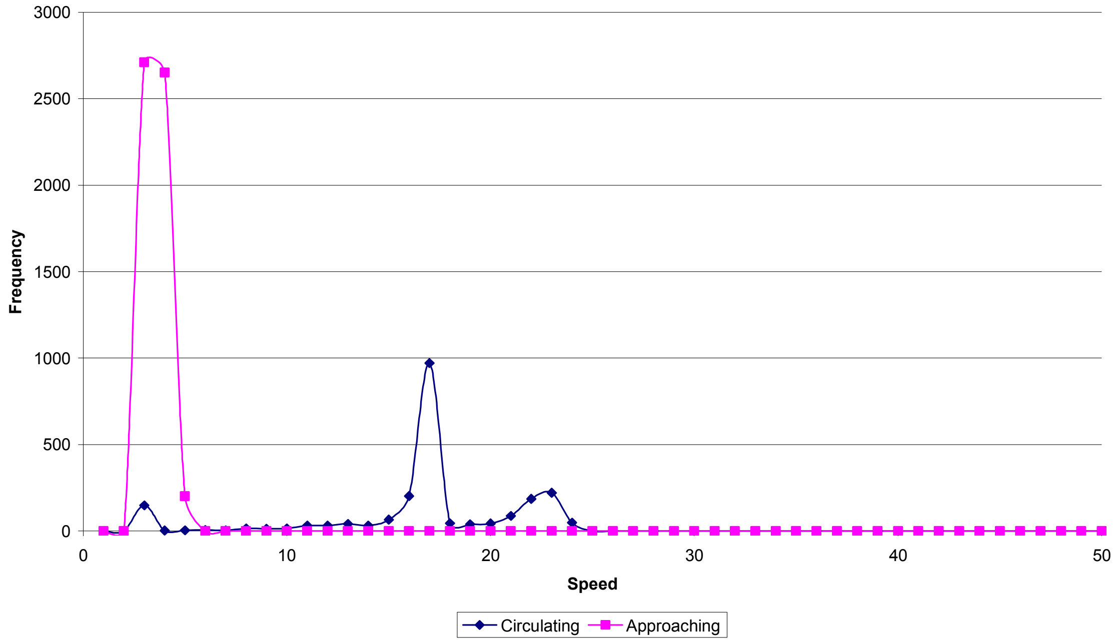


Figure 36. Rt. 130 SB speed distributions – Case 5

Although the circulating speeds remain consistent between cases the approaching speeds drop substantially. In this case the approaching speed is approximately 5 MPH. This is a very good situation.

Cases 4 and 5 shift the traffic over the upgraded Old Salem Road. Whereas in Cases 1, 2, and 3 vehicles bound for Creek Road coming from the north had to follow a path that led them through the circle, in Cases 4 and 5 they make a left onto Old Salem Road prior to reaching the circle. This produces a second benefit of reducing the volume on the approach.

Eastern Circle, Eastbound Entrance

The eastern approach is the connector link from the western circle. The yield is on the approach. Route 130 is the primary route through the entire circle so a large percentage of the traffic at this entrance is coming from Route 130 and passes through the eastern circle onto Route 130 Northbound. Due to this characteristic of the circle there is much more traffic on the approach at this location than on the circulating roadway. The approach speeds during the AM and PM peaks tend to be between 5 – 10 MPH while the circulating speeds are about 22 MPH. This is a good situation. As indicated in the accident history section above there are few accidents associated with the approaching vehicles at this location.

Cases 2-5 all tend to produce similar results due to the fact that no specific changes take place at this location. Cases 4 and 5 have a reduction in the circulating volume because of the allowance of left turns onto Old Salem Road from US 130 southbound. For illustration purposes, Figure 37 shows the speed distribution for circulating and approaching vehicles as a result of Case 5.

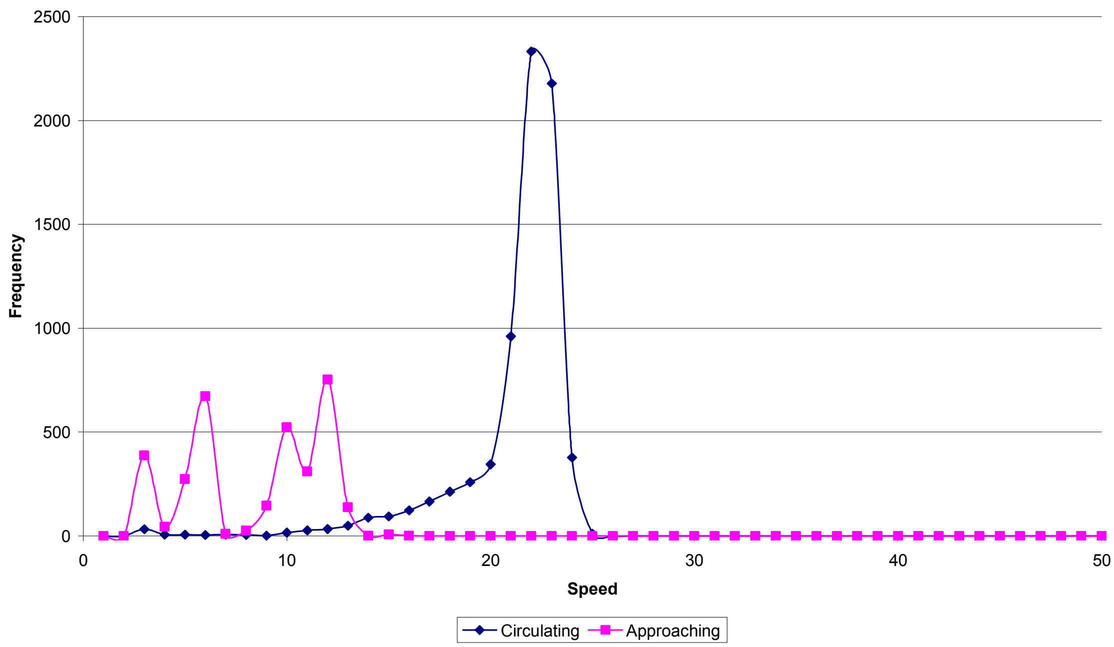


Figure 37. Rt. 130 NB speed distributions – Case 5

Eastern Circle, Southern Leg (NJ 47)

One location where a number of collisions occur is at the southern leg. This is the connection to NJ 47 and Creek Road. The yield at this location is within the circulating roadway. There is also a gas station located at this location. Currently the facility has ingress and egress points within the circle as well as onto NJ 47 and the connector between the two traffic circles. The major conflict point for gas station traffic is on NJ 47. Vehicles can cross the traffic exiting the circle to get to Creek Road.

For Case 1, the speed distributions for the entrance for the PM peak can be seen in Figure 38. The AM peak is similar. The approaching speeds are slightly over 20 MPH. The circulating speeds range between 5 and 15 MPH. Ideally the circulating speed would be more consistent with other points within the circle and the free-flow speeds on the approach and circulating roadway would match.

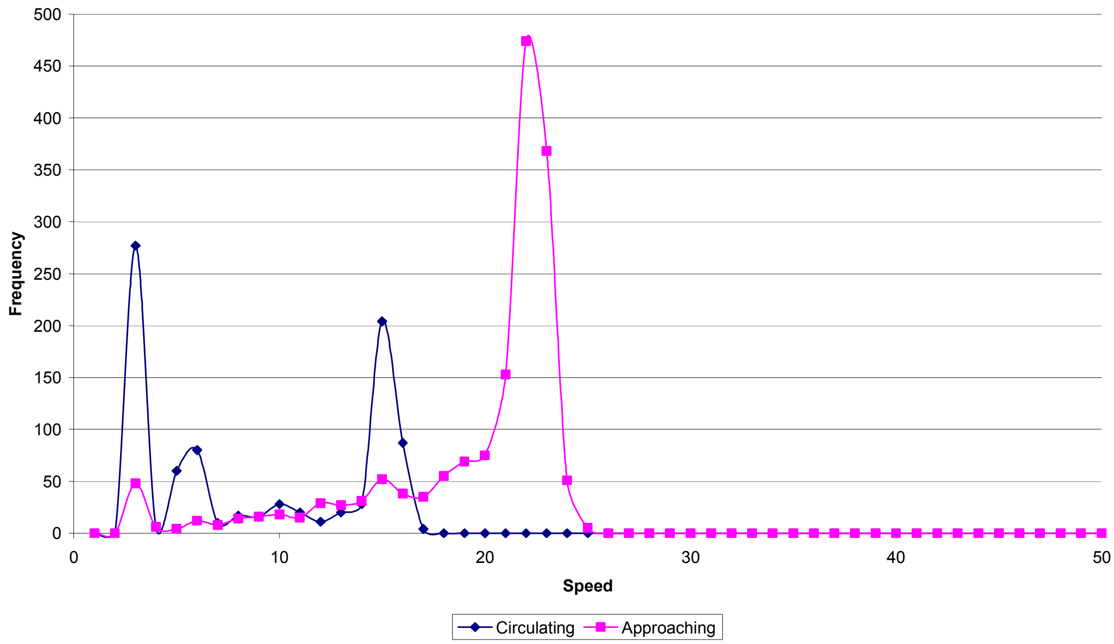


Figure 38. NJ 47 / Rt. 130 NB PM Peak Speed Distribution – Case 1

Cases 2 through 5 eliminate the left turn onto Creek Road by introducing a median barrier. This barrier also prohibits vehicles from turning left from the gas station onto NJ 47. These alternatives also eliminate right turns from Creek Road to the circle. Vehicles must use an upgraded Old Salem Road and access the circle from the north. These changes are expected to reduce the number of vehicles both exiting and entering the circle on this leg.

Case 2 indicates that similar patterns would exist with a slight reduction in volume. The only noticeable change for both cases was a sharper peak in the circulating speed at about 15 MPH. This case is still not desirable because of the large variation between the free-flow speeds.

Case 3 introduces geometric enhancements. It improves conditions slightly during the afternoon peak, but still produces significant differences in free-flow speeds in the AM peak as shown in Figure 39 and Figure 40.

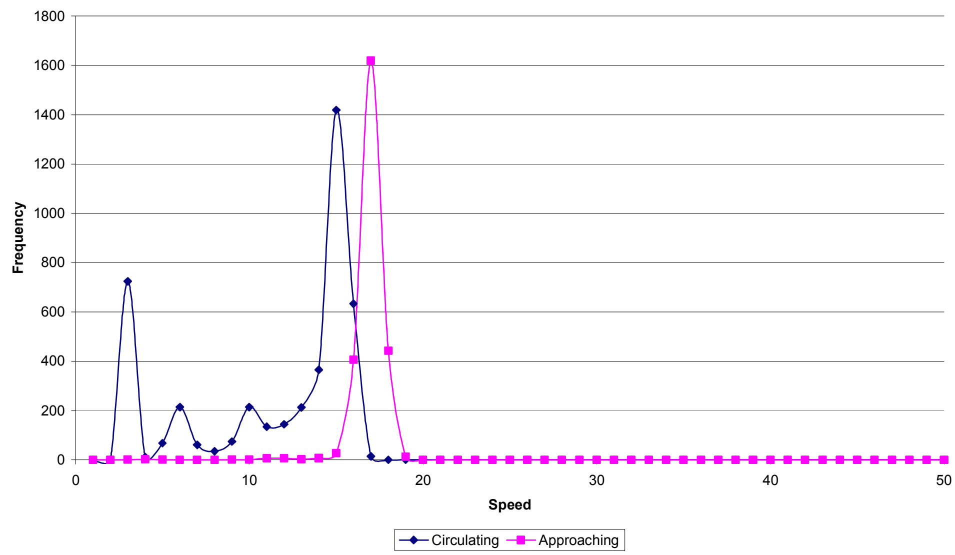


Figure 39. NJ 47 / Rt. 130 NB PM peak speed distributions – Case 3

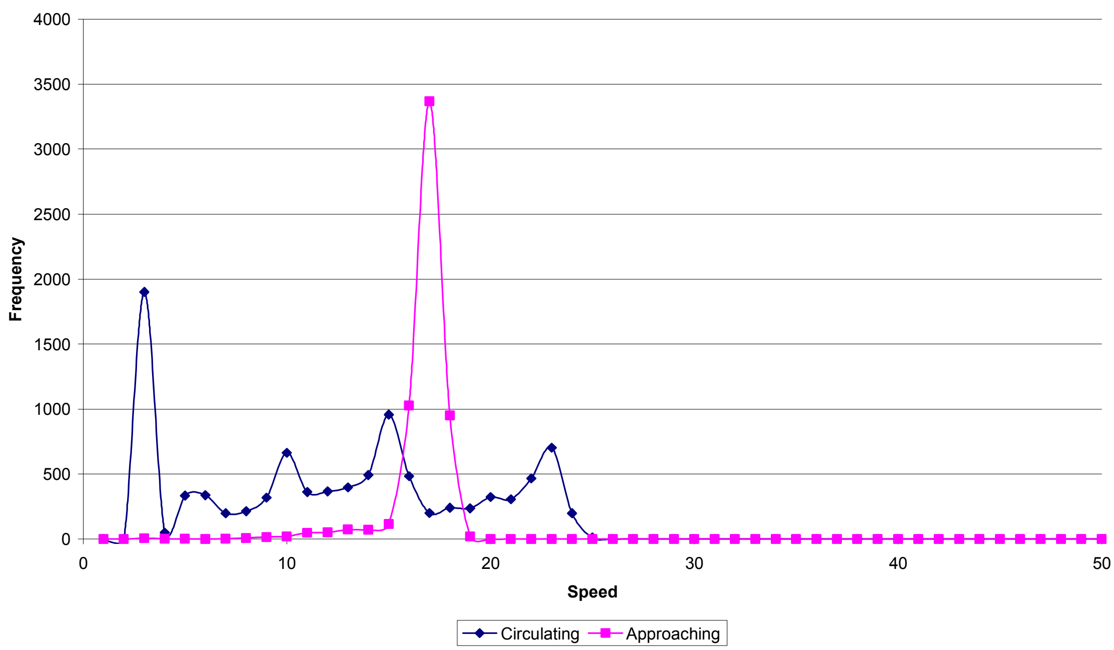


Figure 40. NJ 47 / Rt. 130 NB AM peak speed distributions – Case 3

Case 4 produces results similar to Case 3.

Case 5 moves the yield control to the approach. This change produces ideal results for both the AM and PM peaks. Figure 41 shows the speed distributions after incorporating this change for the PM peak. Both the approaching and circulating speeds are between 20 and 24 MPH.

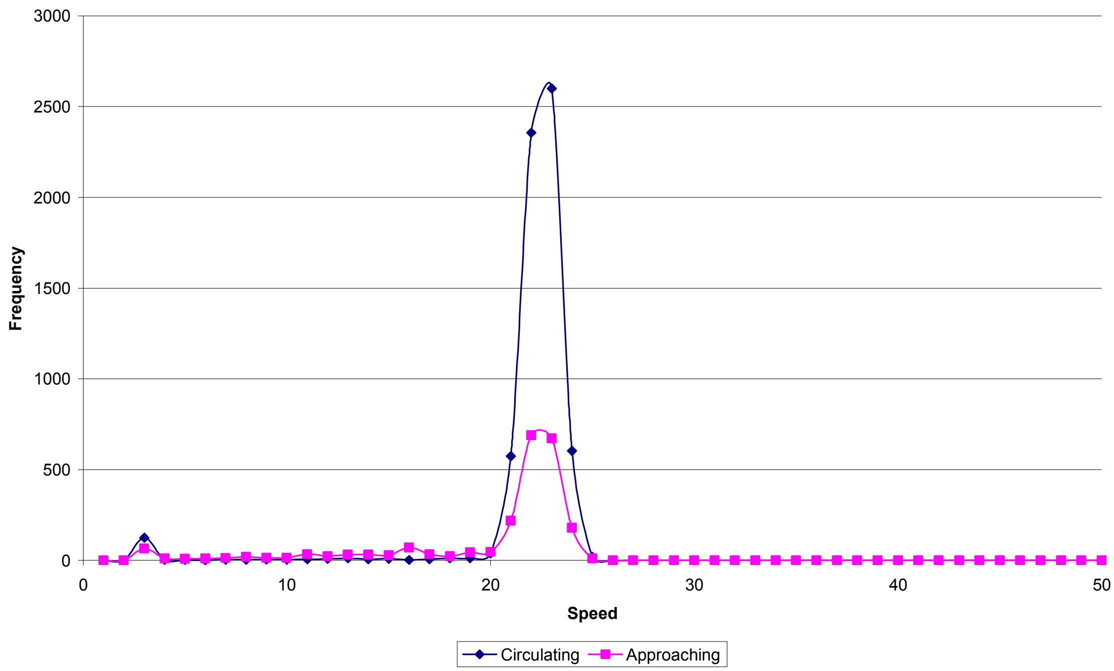


Figure 41. NJ 47 / Rt. 130 NB PM peak speed distributions – Case 5

It is also important to look at changes in speeds as vehicles travel through the facility. Therefore, speed trajectories were examined for each origin-destination pair in the traffic circle to look at how vehicles travel through the circle. The example shown below is for vehicles going from the northbound entrance (NJ 47) to the eastbound exit (US 130 North). Figure 42 below shows the speed trajectory of vehicles making this movement in Case 1 under existing conditions.

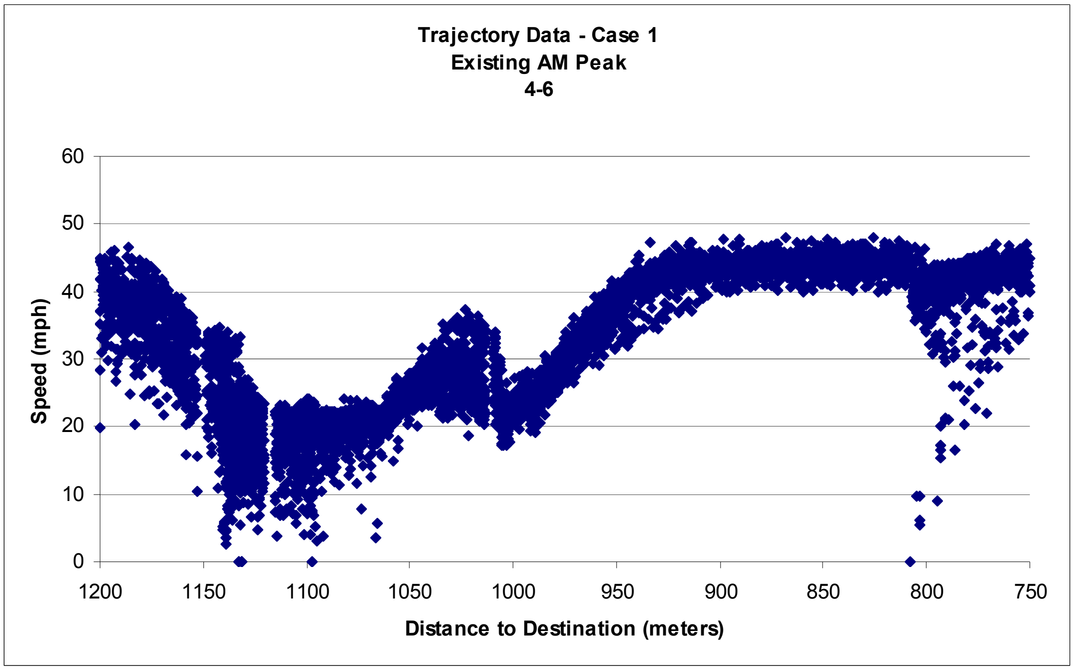


Figure 42. Speed trajectory, NJ 47 to Rt. 130 north of the circle – Case 1

The section of the plot that pertains to the circle is from 1000 m to 1130 m on the "Distance From Start" scale. This is because the PARAMICS model includes intersections both upstream and downstream of the circles. As indicated by the graph, the approaching speed on NJ 47 varies between 0 to 30 MPH. This wide variation in speeds has to do with the conflicts at Creek Road. Also, the speeds within the circle vary between 0 to 22 MPH.

Cases 3 and 4 produce identical results in the area of the traffic circle and slightly better results in Case 4 at the new upstream signal at Old Salem Road. Figure 43 shows the speed trajectory of vehicles making the same movement during Case 4. The approaching speeds range between 10 – 20 MPH can be seen by the speeds shown between 1200 m and 1130 m. In Case 1 for the existing conditions this range was between 10 – 25 MPH. The circulating speeds are fairly consistent with the existing conditions. The new scatter that is between 950 and 800 m is due to the traffic signal at Old Salem Road.

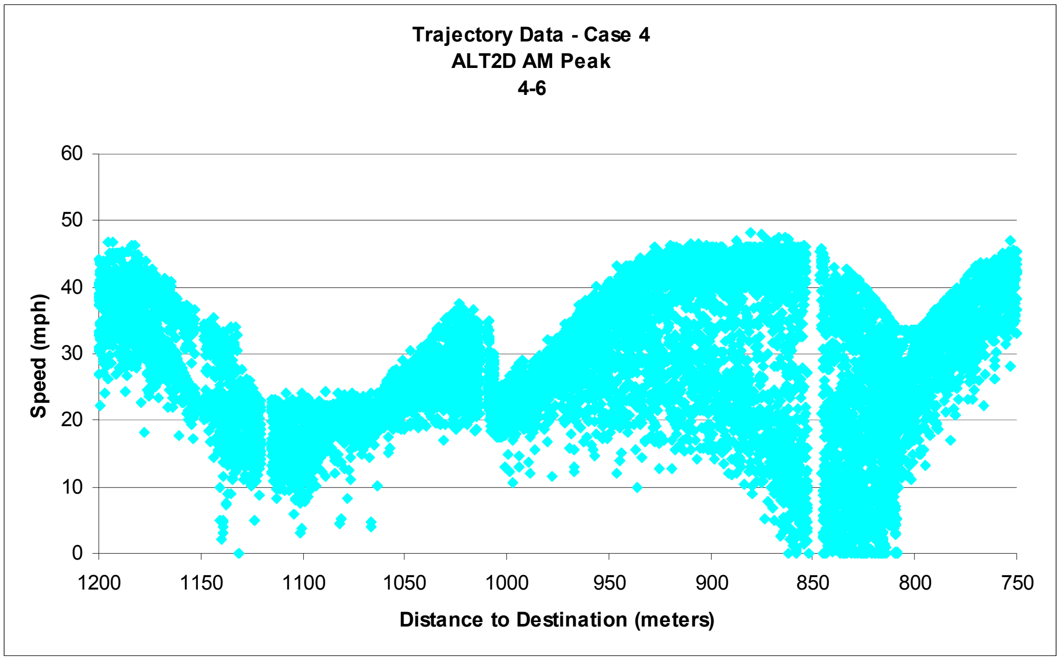


Figure 43. Speed trajectory, NJ 47 to Rt. 130 north of the circle – Case 4

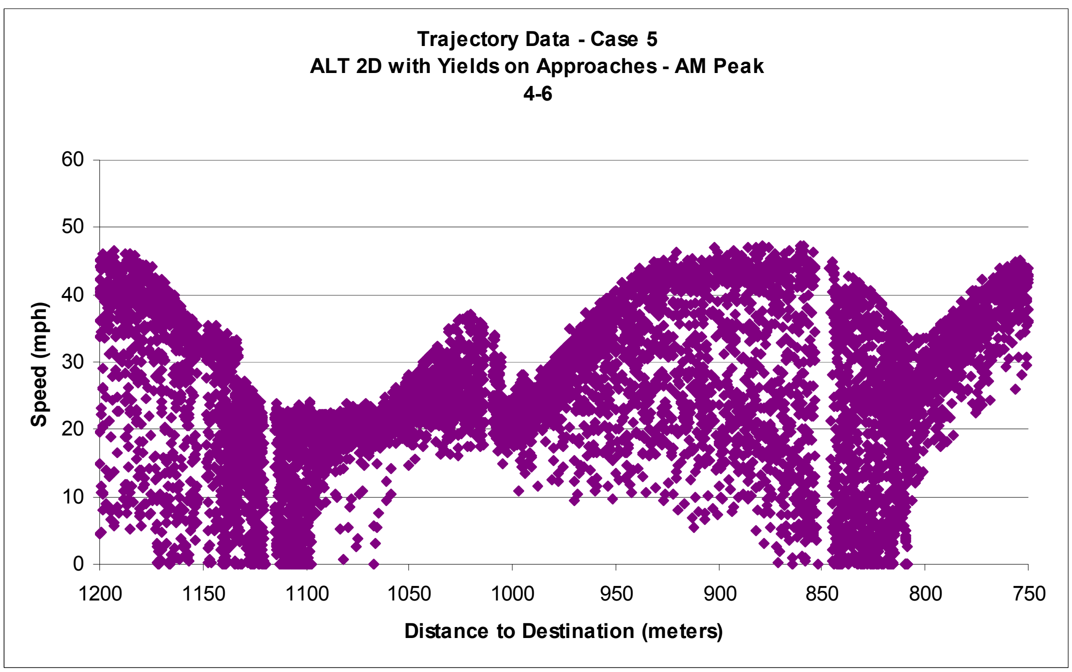


Figure 44. Speed trajectory, NJ 47 to Rt. 130 north of the circle – Case 5

Case 5 produces the results shown in Figure 44. The significant change is that the variability in the approaching speeds is much greater but the circulating speeds are more closely distributed around 20 MPH.

An additional outcome of changing the geometry at Creek Road and NJ 47 is the redistribution of traffic through the network. Presently, traffic originating on Creek Road that is bound for Route 130 north must use the circle. These vehicles must merge onto NJ 47, enter the circle and exit on 130 NB. With the introduction of the traffic signal at Old Salem Road these trips bypass the circle.

Figure 45 and Figure 46 show the trajectories for this movement for both Case 1 and Case 4.

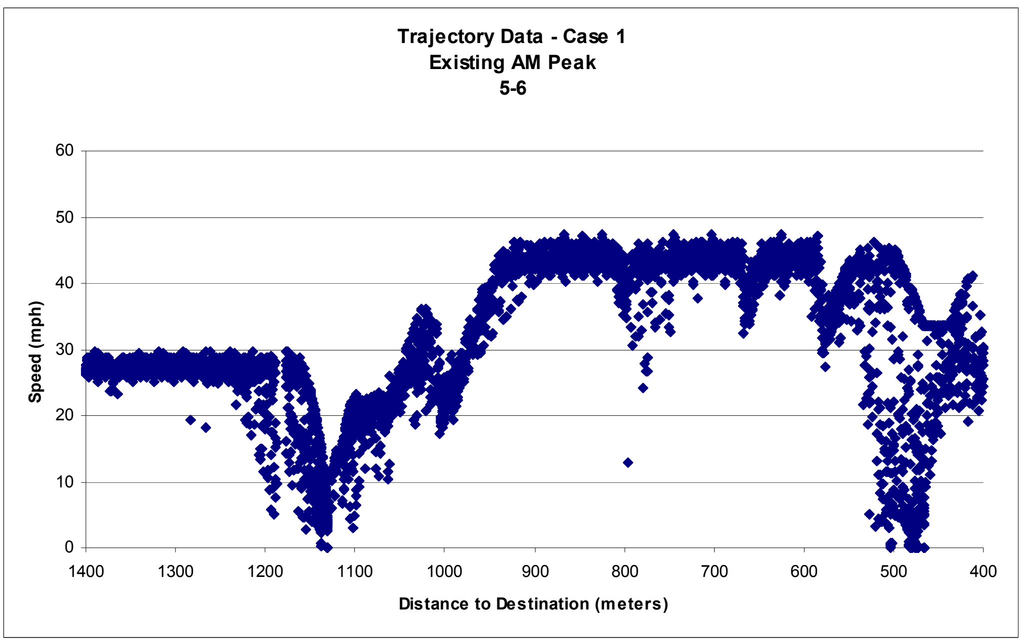


Figure 45. Speed trajectory – Creek Road to Rt. 130 north of circle – Case 1

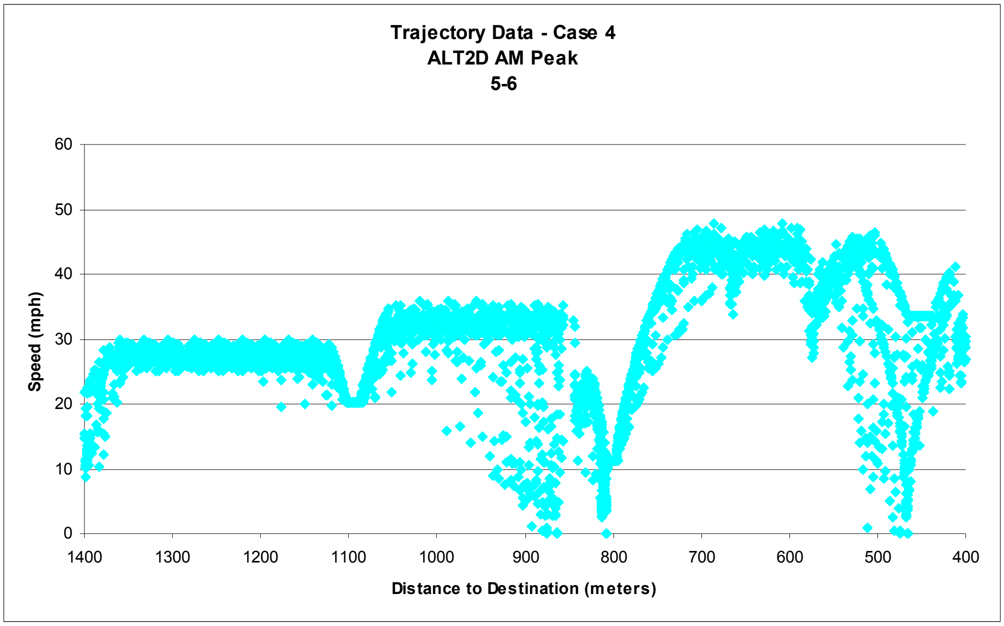


Figure 46. Speed trajectory – Creek Road to Rt. 130 north of circle – Case 4

In Case 1, the vehicles approach the merge point with NJ 47 at 1200 meters and then proceed through the circle between 1150 and 1000 m. The vehicles then exit the circle and proceed north on Route 130. In Case 4, the traffic on Creek Road is between 25 – 30 MPH and turns left onto Old Salem Road at approximately 1100 m on the Distance to Destination axis. The vehicles then travel between 30 – 35 MPH on Old Salem Road until they decelerate for the traffic signal with Route 130. The results of Cases 3, 4 and 5 all produced similar results, this is because the turning movement at the traffic signal does not change.

Western Circle, Southbound Entrance (New Broadway Avenue)

The southbound entrance on the western circle (New Broadway Avenue) has a yield on the approach. The speed distributions at this location are similar regardless of time of day for all the cases of interest. The circulating speeds tend to be between 20 and 22 mph. The approaching speeds tend to be between 5 and 15 MPH. This is a good situation.

Western Circle, Westbound Approach (Connector)

This approach is for the connector between the two circles. It carries traffic destined for Route 130 southbound and New Broadway Avenue. The only conflicting traffic at this point is small amount of traffic going from Route 130 northbound to New Broadway Avenue. Therefore, the approaching traffic can typically enter unimpeded. For Case 1, the approach speeds are slightly over 20 MPH.

Since Case 2 does not have any specific changes at this location there are no noticeable changes in the speed profiles. Cases 3 and 4 maintain a similar pattern but the approaching speeds reduce to approximately 18 MPH for both the AM and PM conditions. Case 5 changes the pattern significantly. The change is due to the fact that the yield control is moved to the approach. Although the circulating traffic is not very high the approaching speeds drop substantially.

Western Circle, Northbound Approach (Route 130 NB)

Currently there are no formal yield signs at this location. This may pose a problem for motorists who are unfamiliar with the facility but since the circulating volumes are substantially lower there is a low occurrence of incidents at this location.

For Case 1, existing conditions, the speed distributions are shown in Figure 47. There is a high degree of variation in the existing approach speed. It ranges from 5 to 22 MPH. The approaching volume at this location is substantially higher than the circulating volume.

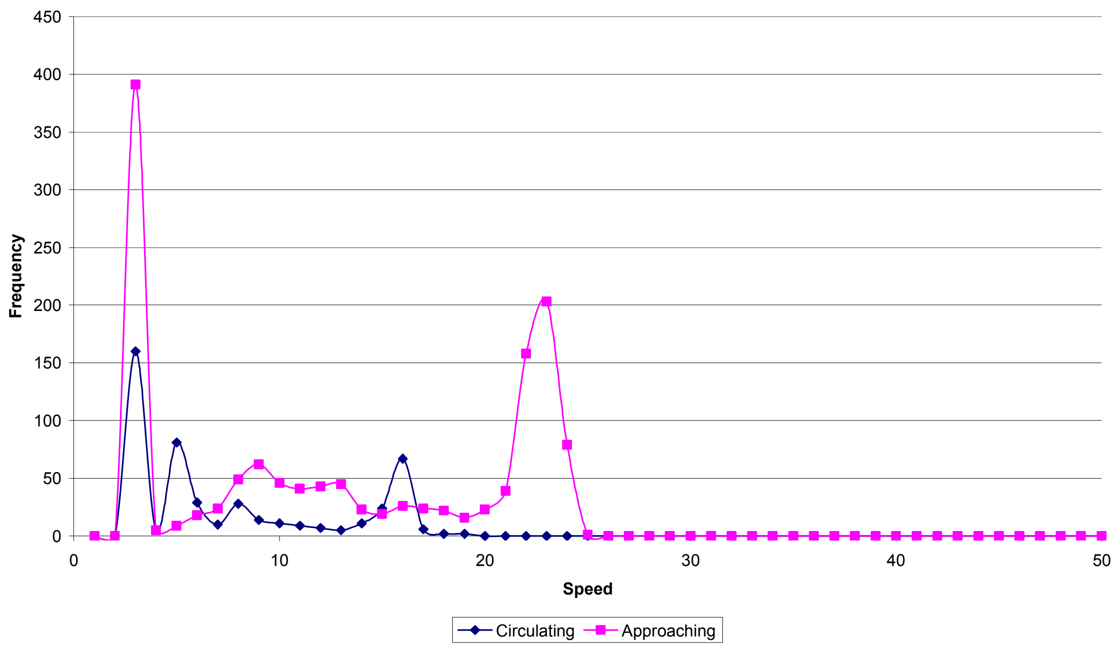


Figure 47. Rt. 130 NB at West Circle speed distributions – Case 1

The figure clearly shows several predominant speeds for both the approaching and circulating vehicles.

Cases 2, 3 and 4 produce similar results. The only changes are for Cases 3 and 4 where some geometric enhancements are introduced to reduce approach speeds.

Case 5 places the yield on the approach at this location. The speed distribution for this case can be seen in Figure 48. This reduces the speeds and produces similar speeds between the approaching and circulating speeds.

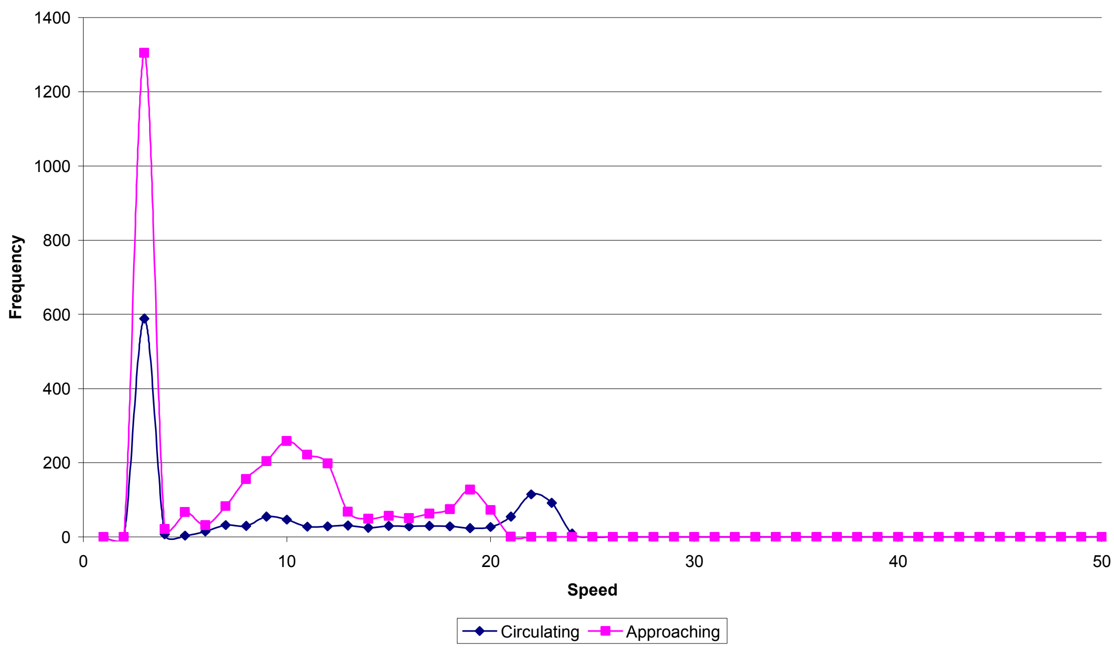


Figure 48. Rt. 130 NB at West Circle speed distributions – Case 5

Brooklawn Circle Conclusions

This chapter discusses the improvements from various safety treatments for the Brooklawn traffic circles in New Jersey. The circles are assessed using a carefully developed safety analysis methodology. Both the empirical models and traffic simulations tested support the proposition that safety will be increased with implementation of the proposed treatments. There is clearly a need to address the accidents that occur at the eastern circle.

Case 1 is the existing conditions.

Case 2 changes the flow patterns associated with reaching Creek Road by introducing an enhanced intersection between Old Salem Road and Route 130 north of the eastern circle. It reduces some of the accidents in the vicinity of NJ 47 and also changes the traffic patterns slightly. However, the speed distributions in the traffic circles are still not desirable.

Case 3 builds on Case 2 by introducing additional enhancements to problematic locations. In order to improve safety, these enhancements aim to reduce speed on the approaches and maintain a uniform speed within the circle.

Case 4 builds on Case 3 by further changing the traffic patterns by allowing key turning movements at the Route 130 / Old Salem Road intersection. The results of this scenario are similar to Case 3 while redistributing traffic patterns through the network.

Case 5 incorporates all of the changes identified in Case 4 and moves all of the yield controls to the approaches. This option significantly reduces the approaching speeds.

Asbury Park Traffic Circle Analysis

In this section, the Asbury Park traffic circle is analyzed. The *Safety Methodology* chapter provides an overview of the process, which included the simulation analyses, the empirical analyses, comparison of these results and a benefit/cost analysis. At the end of this section there are recommendations for the Asbury Park traffic circle based on the quantitative and qualitative assessments.

Study Location

The Asbury Park traffic circle located in Monmouth County, New Jersey is actually a circle within a circle. A plan view of the facility is shown in Figure 49. It is the junction of two major roads, Route 35 and Route 66. There are also numerous local streets and driveway cuts that connect to the circulating roadway. This facility services more than 20,000 vehicles per day with 2 to 4 lanes of primarily concrete pavement. Striping is not prevalent on the facility creating some confusion as to where lanes should be and their assignment.

Figure 49. Asbury Park traffic circle

Accident History

Crash diagrams for all crashes during 2002 have been created for the traffic circle based on the police reports provided by the NJDOT. Typically at least three years of accident data are necessary to see patterns, but there were ample reports to see patterns for just this one year. These diagrams provide insights for each accident, such as the location, type of accident, time of day, weather conditions and severity. Based on the accident patterns, a set of proposed treatments have been developed.

Between January 1, 2002 and December 31, 2002 seventy-two recorded accidents occurred within the Asbury Park traffic circle. A collision diagram was prepared to determine accident patterns in the facility during this time frame, it can be seen in Figure 50. In addition, a database was created that contains the following information about each collision: location of collision, type of collision, number of injuries, number of fatalities, road surface conditions, light conditions, date of collision, apparent contributing factors, and secondary causes of collision. Based on the collision diagram and the accident database, a number of accident patterns were discovered and are discussed in the following paragraphs.

Automobile accidents were 97 percent of the total. Commercial vehicles and buses were involved in the remaining 3 percent. Approximately 24 percent of the accidents occurred when the road conditions were wet or icy. Most of the accidents took place during daylight hours, comprising 75 percent of the accidents. Only 10 percent of the accidents occurred during both darkness and when there were wet road conditions.

None of the accidents produced a fatality but there were 10 injuries. Injuries occurred approximately 13 percent of the time. The most problematic location was in the vicinity of the center circle. Approximately 63 percent of all the accidents were related to vehicles in this area. Other statistics related to the type of accidents encountered at the circle are:

- 7 of 72 (10%) involved "fixed object" collision
- 11 of 72 (15%) involved "angle" collisions
- 17 of 72 (24%) involved "same direction side-swipe" collisions
- 32 of 72 (44%) involved "rear-end" collisions

It should also be noted that approximately 70 percent of the recorded accidents were due to driver inattention.

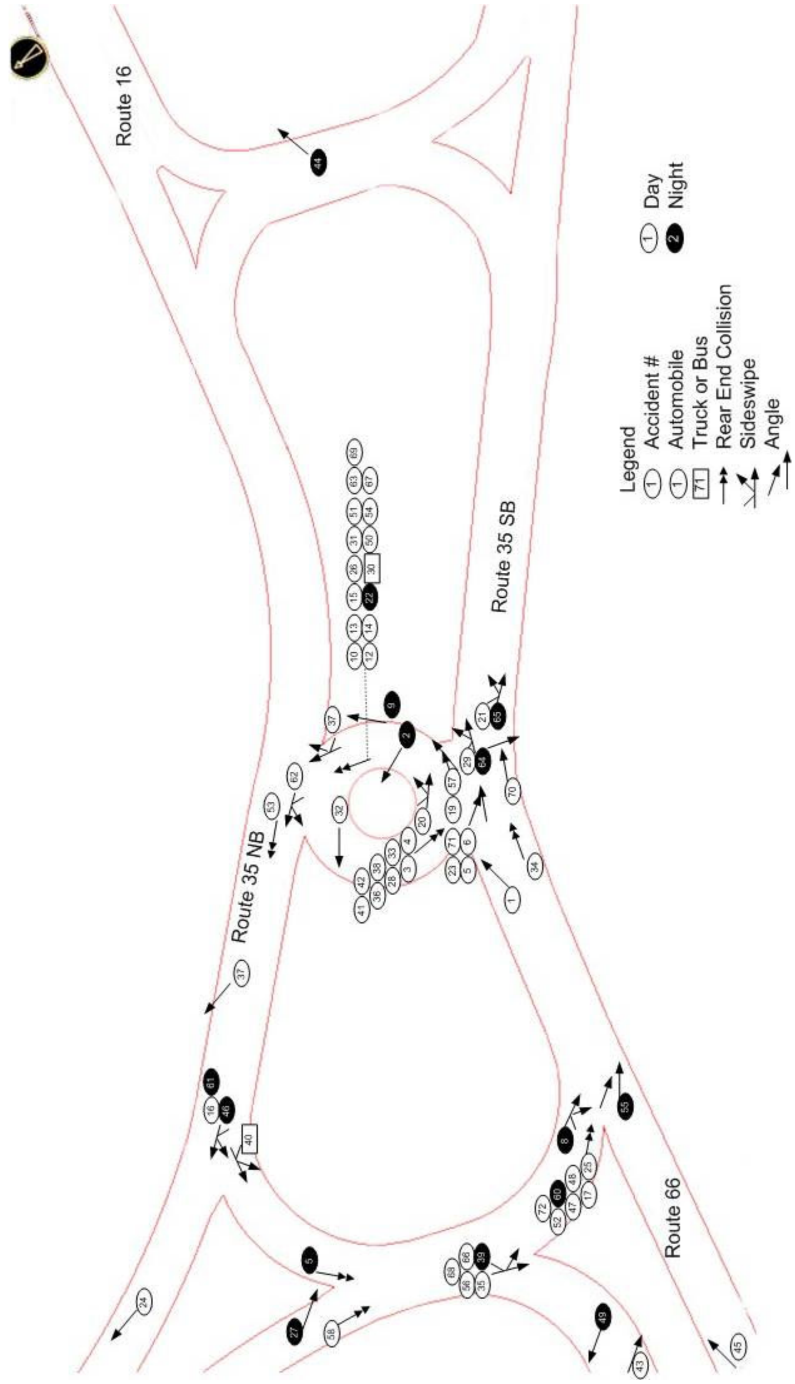


Figure 50. Asbury Park collision diagram (2002)

Inner Circle at Route 35 Northbound (north side of small circle)

This location is where the inner circle intersects with Route 35 northbound. One of the main contributing factors to the problems at this location is due to the large difference in speeds between the large circle and the inner circle. At this location the vehicles at the inner circle must yield to the outer circle.

During 2002 there were 21 accidents in this vicinity. Seventy-two percent (72% or 15 accidents) of these accidents were rear-end collisions with vehicles entering the back of queue within the small circle. Of these accidents 4 were when the roadway was wet and all but one was during daylight hours. Most all of the rear-end collisions were due to driver inattention. There were also 3 accidents what were single vehicle accidents that struck the curb within the center circle. There was only one recorded collision due to a driver entering the small circle from the Route 35 north.

Route 66 Westbound Diverge from Route 35 Southbound

During the one year period, five accidents were recorded where Route 66 westbound diverges from Route 35 southbound; all of these accidents were sideswipes and one involved injuries. Also, on the Route 66 westbound exit leg there were two fixed object accidents.

Route 66 Eastbound at Route 35 Southbound

This location is where Route 66 eastbound meets Route 35 southbound. At this location both Routes 66 and 35 are two lane facilities and the yield is located on Route 35 south. The approaching speeds from Route 66 are fairly high because prior to entering the circle the speed limit is 55 mph and the road is quite straight. Cardinal Road is also located across from the yield sign. This road is two-way so movements going to and coming from here can create problems.

There were 9 total accidents in this vicinity during 2002. Seven accidents were rear-end collisions on Route 35 south approaching the yield sign. Three of these accidents produced injuries. There was also one angle collision and one sideswipe accident due to drivers failing to yield.

Route 35 Southbound Approach

During 2002, three accidents occurred on the Route 35 southbound approach. Two of the accidents occurred at night. Two accidents were rear-end collisions and one was with a fixed object.

Route 35 Northbound Diverge

The Route 35 northbound diverge produced four accidents during 2002. All of these accidents were sideswipes due mainly to driver inattention.

Inner Circle at Route 35 Southbound (south side of small circle)

The south side of the inner circle produced the largest number of accidents. These accidents were associated with vehicles traveling both within the inner circle, Route 35 southbound on the outer circle and entering and exiting nearby driveways at many local businesses.

Twenty-two accidents occurred in this area, comprising 31 percent of all the accidents at the Asbury Park traffic circle in 2002. Eight of these accidents occurred at the back of queue at the yield sign within the inner circle. These accidents were due to driver inattention. There were also four collisions with vehicles exiting the inner circle and colliding with vehicles attempting to access the inner circle. There were also three other accidents that were due to vehicles attempting to access the inner circle from Route 35 south.

The large number of driveway cuts and local streets connecting to the circle in this area also present many additional accidents. These accidents are mainly due to drivers trying to maneuver from both the inner and outer circles to the business establishments. There were approximately six accidents that were due to these maneuvers.

Selection of Safety Treatments

As a result of the of the accident history study, several safety treatments were developed as possibilities for the traffic circle. Those treatments are discussed in the following paragraphs.

Entry Curvature and Deflection

Entry curvature is a main variable contributing to approaching collision frequency. Approaching collisions are a problem particularly on the Route 66 eastbound approach. A main contributing factor to these collisions is high speeds on this approach. Increasing the entry curvature and entry deflection on this approach will require vehicles to slow down as they enter the traffic circle.

The approaching curvature on Route 35 northbound and southbound nearby the center circle is fairly straight, therefore promoting high-speed maneuvers. This causes problems because some vehicles are decelerating to enter the inner circle, while some vehicles are maintaining the higher speeds to continue on Route 35.

It is necessary to reconfigure the entry curvature on all of the high-speed approaches to ensure that vehicles will slow to a safer speed limit within the circle.

Roadway Width

Although not directly evident from the accident history, roadway width is a concern for the Asbury Park traffic circle. The excessive widths encourage high speeds and self-created lanes by drivers potentially resulting in confusion.

However, it may not show up in accidents directly, especially since the pavement condition was “fair” to “good” with several cracks in the concrete (no asphalt at this location).

Speed Limit

A major problem leading to collisions at Asbury Park Circle is the fact that the speed limit on each of the approaches is very different. For example, the posted speed limit on the Route 66 eastbound and Route 35 southbound approaches is 50-mph, while the speed limit on the Route 16 westbound approach is 35-mph. There are also many local streets that distribute to the main circle with much lower posted speed limits. This creates a greater relative difference in speeds between movements in the traffic circle, leading to greater risk of collision. This can be seen in the presence of frequent collisions at the entrances and exits where vehicles are traveling at different speeds. Decreasing high speed limits thereby making all the speed limits more uniform can reduce these collisions. For a smaller traffic circle or roundabout it is typically good practice to match the speeds on all of the approaches. In this case since the facility is so large and the street types vary so much it is recommended to reduce the speeds on the approaches to a reasonable limit such as 35-40 mph on the main approaches and keep the speeds consistent throughout the facility.

As stated earlier there are numerous local roads and driveways that have direct access to the main circle. In order to maintain uniform speeds throughout the circle it is suggested that acceleration and deceleration lanes be provided for these roads and establishments. This would ensure that vehicles with changing speeds would not impede the main traffic flow of the circle.

It is important to note, however, that simply reducing the speed limit on the approaches will not necessarily reduce the speeds by a significant amount. There needs to be a perceived need by the drivers for speeds to be reduced accompanying the reduction in speed limits. Therefore, reduction of the speed limit should be accompanied by reduction of the roadway width on the approach and/or introduction of a curve approaching the circle to require vehicles to reduce speeds upon approach.

Advance Warning Signs

Due to the complexity of the road network entering the facility, it is recommended that all drivers be aware they will be entering a complex traffic circle. There is currently little signage prior to entering the circle indicating to the motorist that they will be entering such a facility. Most of the signage is currently within the circle and requires unfamiliar motorists to study the signs while maneuvering through the facility.

Advance warning signs stating “Traffic Circle Ahead” should be placed on all approaches in advance of the traffic circle. These signs should be accompanied by “Reduce Speed Now” signs to encourage drivers to slow down approaching the circle. In addition to not recognizing that a traffic circle is ahead, drivers often do not know which lane they should use in order to make their desired movement through the circle. Placement of map-like navigation signs on each approach in advance of the traffic circle could reduce this problem. An example of this type of sign is shown in Figure 51 below.

Figure 51. Directional traffic sign

Right-of-way

Another issue with the Asbury Park Circle is that entering traffic on the outer circle has the right-of-way on all approaches. Within the inner circle the right-of-way is given to the vehicles traveling on the outer circle. This allows vehicles to enter the circle at very high speeds, while traffic inside the circle is traveling at low speeds. This speed differential creates a high risk of collisions. Also, requiring vehicles to stop or yield in the circulating roadways leads to queues and greater accident risk in the traffic circle. The presence of frequent rear-end collisions on the yield lines, especially where Route 35 southbound yields to Route 66 westbound exiting traffic, further proves this point. From an operational standpoint, having queues inside the traffic circle can create significant delays as opposed to leaving queues on the approach. For example, if a queue occurs within the traffic circle, this queue can back around the entire circle causing gridlock. However, if queuing occurs on an approach, operations can be maintained on the remaining approaches. From a safety perspective, when a rear-end collision occurs at a yield point inside the circle, gridlock and further collisions are likely to occur. However, if this collision occurs on the approaching roadway, a queue is created on that approach, but traffic elsewhere continues moving smoothly. Therefore, a solution to the issue of right-of-way would be to give the right-of-way to the circulating traffic and place yields on the approaches. It is also recommended to eliminate the center circle. This would eliminate the confusion of right-of-way at the center circle and the neighboring driveways as well as provided more uniform travel throughout the facility.

Not only does giving the right-of-way to circulating vehicles reduce the risk of rear-end collisions at conflict points inside the circle, it also requires vehicles entering to slow down in order to yield to circulating traffic. This thereby, reduces overall speeds in the facility and reduces the relative difference in speeds between circulating, entering, and exiting traffic.

Striping

The Asbury Park traffic circle contains no striping within the traffic circle itself. This creates some confusion as to which lanes a driver is able to use to make a desired movement. In addition, it creates confusion over how many lanes the circle actually contains. At times, drivers use the circle as though it contained three lanes, while at other times the circle is used as though it contained two lanes. The lack of striping forces drivers to vie for positions in the circle, which leads to several sideswiping collisions. Striping indicating lane usage may reduce such collisions. It may also be helpful to strip acceleration and deceleration lanes near the local streets and driveway cuts, as mentioned earlier.

Driveway Cuts

Within the traffic circle there are many commercial establishments. Many of these establishments have driveway cuts directly into the circle. When possible these driveway cuts should be removed.

Examples include the Exxon gas station and Blockbuster Video store on Route 35 southbound directly across from the inner circle. There are multiple driveways in this area. There is one where customers can safely enter the circle and proceed around the circle. These establishments seldom have common access points, rather they have multiple driveways. If these driveways could be consolidated with some of the other local establishments and distributed to the local roads that would eliminate some of the collisions within the circle.

In summary, the following treatments are recommended to increase safety:

- Increase entry curvature and entry deflections on the Route 66 approach and the inner circle approaches.
- Reduce speed limits to 35 or 40 mph and add YIELD signs to all major outer circle approaches.
- Remove YIELD signs within the outer circle; add YIELD signs to any inner circles' approaches to the outer circle.
- Add lane striping throughout the circle.
- Add acceleration and deceleration lanes in the outer circle for all minor approaches.
- Reduce the number of driveway cuts that access the outer circle.
- Add warning and directional signage to assist drivers entering and traveling through the facility.

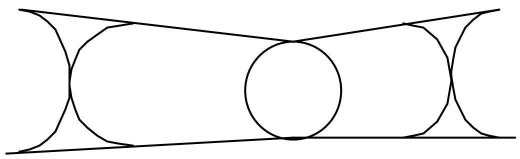
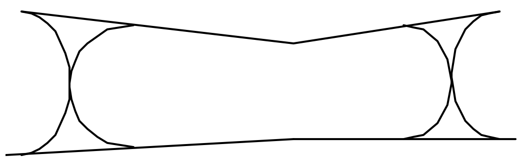
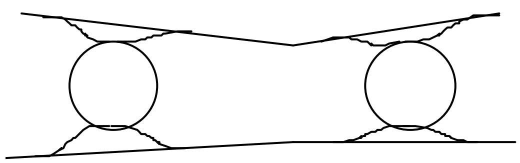
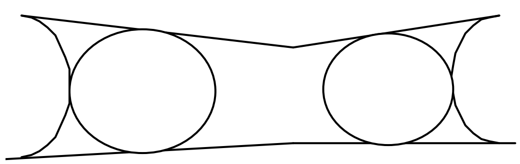
Empirical Analysis

Supplementing the safety analysis based on the accident histories is an assessment based on the empirical models discussed in the *Review of Safety Models* chapter (see page 17) that predict accident frequencies. Several of the recommendations from the last section were incorporated into a handful of alternative designs for the Asbury Park traffic circle. Next is a short subsection that includes the various designs.

Alternative Designs Initially Considered

Five designs were considered as shown in Table 20 and compared on the basis of what recommended treatments they instituted. The designs of course also vary with respect to cost and complexity of construction. For example, although Alternative B may include all the recommended treatments it would be an expensive option to build. Likewise, Alternative D would be quite costly to implement while also being potentially confusing to infrequent facility users. Alternative A was decided against because without the inner circle or additional arcs connecting the north and south straight-aways drivers would incur longer travel times for the majority of traffic movements. Hence, Alternative C (with its low cost changes) was chosen as the design to be tested against the Existing Condition for this study.

Table 20. Potential alternative designs for the Asbury Park traffic circle.

Design	Recommended Treatment					
	Reduce Driveway Cuts	Increased Entry Curvature	Speed Limits Reduced	Outer Circle No Yields	Add Accel/ Decel Lanes	Inner Circle Yields
Alternative No Change: Existing Condition 						
Alternative A: Removal of Inner Circle 			✓	✓		
Alternative B: Two Circles with Bypass Lanes 	✓	✓	✓	✓	✓	✓
Alternative C: Creation of Two Large Circles 		Route 35 ✓	✓	✓		✓

Average Annual Daily Traffic Estimates

To calculate the empirical models, average annual daily traffic (AADT) volumes are needed; therefore, the AADTs were calculated for both the existing case and the alternative of primary interest, Alternative C. Figure 52 and Figure 53 include the requisite traffic volumes. As can be seen in the existing case (Figure 52), daily volumes are highest on the straight-aways with 18,000 to more than 22,000 vehicles per day (vpd). The central circle has the smallest volumes with less than 5,000 vpd circulating. Although there are a low number of vehicles traveling through the central circle, it was found during the team's fieldwork that long queues develop to enter the central circle, causing considerable speed differentials between vehicles on the straight-aways. To reduce the speed differential and queues on the outer circle, Alternative C was introduced for comparison. Figure 53 shows the change in configuration from the existing condition to Alternative C; the major difference is the removal of the central circle replaced by two links to create two larger circles at either end of the Asbury Park circle enabling longer queues to occur within the sub-circles while reducing the speed differential on the straight-aways and keeping this differential closer to the traffic circle approaches where speeds are typically lower.

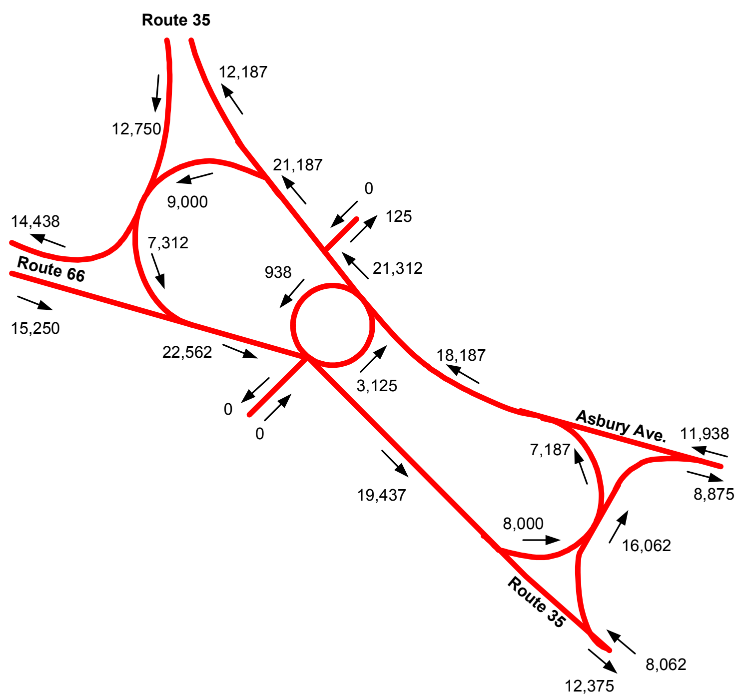


Figure 52. Asbury Park Traffic Circle Existing Conditions estimated AADTs

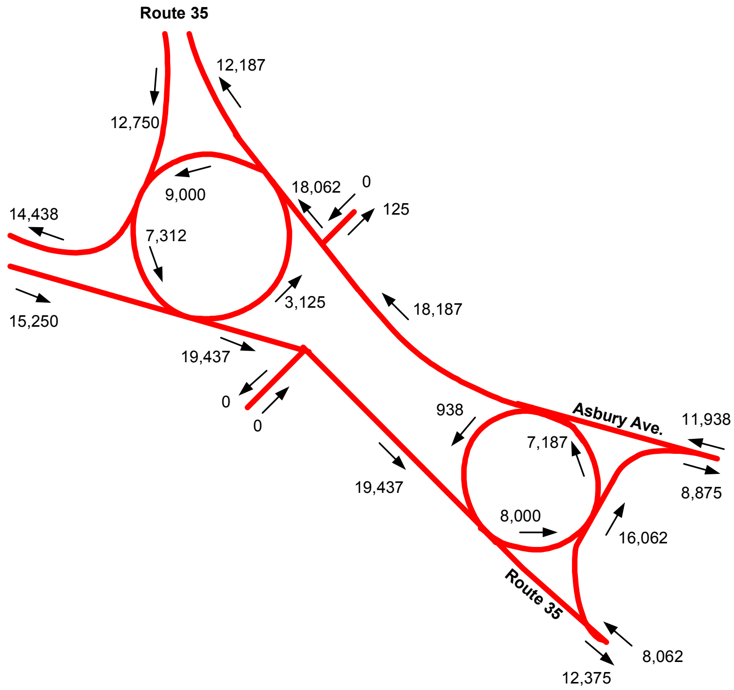


Figure 53. Asbury Park traffic circle Alternative C estimated AADTs

Maycock & Hall (1984) [1]

As can be deduced by reviewing the description of Maycock and Hall's model (see the section titled Maycock & Hall – UK Model (1984) on page 19), predictions of the accident frequencies are dependent upon a number of inputs: the entry (Q_e), conflicting (Q_c), and exiting (Q_{ex}) flows, expressed as AADTs; the curvature (C_e) of the entry (reciprocal of the radius), the entry width (e), the approach width (v), the approach curvature category (C_a), the ratio of the inscribed diameter to the diameter of the central island (R), the percentage of motorcycles in the approach traffic stream (P_m), the angle to the next downstream entry (θ), the gradient category (g), and the sight distance on the approach (V_r). The values of these parameters for each of the approaches in the existing conditions and Alternative C are shown in Table 21, respectively, for the Asbury Park traffic circle. The AADTs are in thousands of vehicles. The angle is expressed in degrees. For consistency, the sight distances that are effectively infinite are set to 500 m. Differences between the two cases are highlighted in the table and include traffic volume shifts and radii changes with the addition of the two new links with larger radii than the removed inner circle.

Table 21. Existing condition & alternative C inputs

Approach Location	Q_e	Q_c	Q_{ex}	C_e**	e*	v	C_a	R	P_m	Θ	g	V_r
EXISTING CONDITIONS												
Rte 35 SE NWB	8.062	8.000	12.375	0.05	7.3	14.6	0	1.25	5	32	0	500
Rte 35 NW SEB	12.750	9.000	12.187	0.02	7.3	14.6	-1	1.21	5	77	0	500
Rte 66 EB	15.250	7.312	14.438	0.00	7.3	14.6	0	1.12	5	152	0	500
Asbury Ave WB	11.938	7.187	8.875	0.02	7.3	14.6	0	1.25	5	101	0	500
Rte 66 EB at Inner Circle / Robyn Rd	22.562	0.938	21.312	0.00	7.3	14.6	0	1.43	5	n/a	0	500
Asbury Ave WB at Inner Circle	19.125	3.125	20.375	0.05	7.3	14.6	0	1.43	5	n/a	0	500
ALTERNATVE C												
Rte 35 SE NWB	8.062	8.000	20.375	0.05	7.3	14.6	0	1.25	5	32	0	500
Rte 35 NW SEB	12.750	9.000	12.187	0.02	7.3	14.6	-1	1.21	5	77	0	500
Rte 66 EB	15.250	7.312	14.438	0.00	7.3	14.6	0	1.12	5	152	0	500
Asbury Ave WB	11.938	7.187	8.875	0.02	7.3	14.6	0	1.25	5	101	0	500
Rte 66/35 to Asbury Ave	19.437	0.938	18.187	0.02	7.3	14.6	0	1.09	5	132	0	500
Asbury Ave to Rte 35	18.062	3.125	19.437	0.02	7.3	14.6	0	1.14	5	132	0	500

* "e" is 12-feet per lane, converted to meters (divide by 3.281).

** "C_e" = $1/R_e$, R_e is the min entry radius for a through movement, based off of PARAMICS radii measurements and typical lane widths.

n/a = angle to next approach is not applicable here because of the nonstandard shape of the facility

x.xxx = input values that change from one alternative to the next

Table 22 presents a comparison of the accident rates predicted by the Maycock and Hall (1984) empirical equations for the Existing Conditions and Alternative C.

Table 22. Estimated accident rates based on Maycock & Hall (1)

Approach Location	Existing*	Alt C	% Change	Existing*	Alt C	% Change
OUTER CIRCLE						
	Entering/Circ			Single Vehicle		
Rte 35 SE NWB	0.056	0.056	0.0%	3.296	3.296	0.0%
Rte 35 NW SEB	0.187	0.187	0.0%	2.744	2.744	0.0%
Rte 66 EB	0.209	0.209	0.0%	1.782	1.782	0.0%
Asbury Ave WB	0.139	0.139	0.0%	2.193	2.193	0.0%
Rte 66/35 to Asbury Ave**	n/a	0.066	n/a	n/a	3.331	-35.6%
Asbury Ave to Rte 35***	n/a	0.098	n/a	n/a	3.137	53.1%
	Approach-RearEnd			Other		
Rte 35 SE NWB	0.463	0.463	0.0%	0.202	0.202	0.0%
Rte 35 NW SEB	0.549	0.549	0.0%	0.308	0.308	0.0%
Rte 66 EB	0.527	0.527	0.0%	0.302	0.302	0.0%
Asbury Ave WB	0.489	0.489	0.0%	0.249	0.249	0.0%
Rte 66/35 to Asbury Ave**	n/a	1.171	-11.6%	n/a	0.080	11.1%
Asbury Ave to Rte 35***	n/a	1.029	51.4%	n/a	0.183	4.2%
INNER CIRCLE						
	Entering/Circ			Single Vehicle		
Rte 66 EB at Inner Circle/ Robyn Rd	n/a	n/a		2.457	n/a	
Asbury Ave WB at Inner Circle	n/a	n/a		6.693	n/a	
	Approach-RearEnd			Other		
Rte 66 EB at Inner Circle/ Robyn Rd	1.049	n/a		0.090	n/a	
Asbury Ave WB at Inner Circle	2.118	n/a		0.191	n/a	

* Existing and all alternatives based on AADTs generated from the OD Tables.
** New link creating west circle
*** New link creating east circle
0.xxx = lower (better) accident rates predicted
0.xxx = higher (worse) accident rates predicted
n/a = not applicable because the intersection does not exist for this alternative
= corresponding approaches between alternatives

It should not be expected that the predicted accident rates would match the observed performance of the traffic circle. The equations are calibrated for British conditions, not American ones; and they are for four-leg, single lane roundabouts; not multi-lane traffic circles with irregular geometry. That having been said, examining the predictions is still valuable, especially the changes in those predictions based on the geometric enhancements proposed.

Based on the empirical results using the Maycock and Hall [(1)] equations (see Table 22 and Table 26), overall safety should improve at the Asbury Park traffic circle with the implementation of Alternative C by an approximately 13.3 percent decrease in the accident rate. Accident rates for all accident types are expected to decrease for the majority of approaches. In particular, two type-location combinations were found to not be fully resolved by the improvements while results are inconclusive for a third combination. First, single vehicle accidents are expected to increase by 35.6 percent (2.457 to 3.331 acc/yr) for vehicles traveling from Route 66 eastbound to Asbury Avenue (Route 16) westbound. It is anticipated that these occur because the entry radius decreases from infinity to 50 meters thereby increasing C_e by an order of magnitude, which negatively impacts the accident rate (raises it). Fortunately, this is an isolated case for single vehicle accident rates which decrease by 14 percent for the entire facility.

Second, approach-rear end accidents are expected to increase by 11.6 percent (1.049 to 1.171 acc/yr) for vehicles traveling on the same link as for the single vehicle accident rate increase. Again for the facility as a whole, approach-rear end accident rates are expected to decrease by 18.6 percent.

Surprisingly, no changes were evident for the Route 35 SE approach although the traffic volume was substantially increased from 12,375 vpd to 20,375 vpd for the exiting flow. According to the Maycock & Hall [(1)] equations, the exiting flow is only included in the pedestrian accident rate calculations, therefore one should not see a change in the other equations. This discovery may warrant further investigation and redesign of the Maycock & Hall [(1)]equations to be more sensitive to the impact of exiting traffic.

It is expected that removal of the inner circle and replacing it with two larger circles reduces single vehicle accident rates the most (such as from 6.693 to

3.137 for Asbury Avenue westbound). In other words, removal of the inner circle simplified two intersections (one less approach for each) thereby making them safer because there are fewer traffic movements possible and potential queues leading into the inner circle no longer exist at these locations; instead, they have been displaced to the new larger circles with greater storage capacities. The new links, route 66/35 north to Asbury Avenue (west large circle) and Asbury Avenue south to Route 35 (east large circle) create two new circles that can effectively operate independently. Their larger diameters enable safer transitions between the main roads and the circles as borne out by the results in Table 22.

***Arndt (1998)*[10]**

Arndt's (1998) model is very different from Maycock and Hall [1]. It is predicated on different data and structured in alternate manner. The accident rate predictions are not likely to be the same. It has not been calibrated for American conditions and it is intended to be used for roundabouts, not traffic circles.

This said, the variable labels are as follows. A_* denotes an accident rate prediction; Q_a is the approach volume (as an AADT divided by 1,000); N_c is the number of circulating lanes; $S(Q_{ci})$ is shorthand for the conflicting volume at a given approach; S_{ra} is the average relative difference in 85th percentile speeds between the approach and the circulating traffic; t_{Ga} is the average time to get from the yield line to the conflict point; S_{ri} and t_{Gi} are identical thoughts for specific approaches; d_{Gi} is the distance in meters from the yield line to the conflict point; N_a is the number of lanes on the approach; L is the length in meters of the horizontal segment for which the single vehicle accident rate is being predicted; S is the 85th percentile speed at the beginning of that segment; ΔS is the change in 85th percentile speed occurring across the segment; and R is the radius in meters of the segment.

The empirical model inputs for the existing conditions and Alternative C are shown in Table 23 followed by the calculated variables in Table 24.

Table 23. Existing condition and alternative C inputs

Approach Location	Q_a (or Q)	$S(Q_{ci})$	$S(Q_{ei})$	S_a	S_{ci}	S	ΔS	N_c	d_{Gi}	L	R	Δfl
EXISTING CONDITIONS												
Rte 35 SE NWB	8.062	8.000	12.375	32	24	64	10	2	10	10	20	0.5
Rte 35 NW SEB	12.750	9.000	12.187	40	32	64	5	2	10	10	52	0.5
Rte 66 EB	15.250	7.312	14.438	56	32	64	10	2	10	10	500	0.5
Asbury Ave WB	11.938	7.187	8.875	48	24	64	10	2	10	10	52	0.5
Rte 66 EB at Inner Circle/ Robyn Rd	22.562	0.938	21.312	40	16	40	5	2	10	10	500	0.5
Asbury Ave WB at Inner Circle	19.125	3.125	20.375	40	16	40	10	2	10	10	20	0.5
ALTERNATIVE C												
Rte 35 SE NWB	8.062	8.000	20.375	32	24	64	10	2	10	10	20	0.5
Rte 35 NW SEB	12.750	9.000	12.187	40	32	64	5	2	10	10	52	0.5
Rte 66 EB	15.250	7.312	14.438	56	32	64	10	2	10	10	500	0.5
Asbury Ave WB	11.938	7.187	8.875	48	24	64	10	2	10	10	52	0.5
East Circle approach from Rte 66	19.437	0.938	18.187	40	48	64	10	2	10	10	500	0.5
West Circle approach from Asbury Ave	18.062	3.125	19.437	40	48	64	10	2	10	10	500	0.5

x.xxx = input values that change from one alternative to the next

Table 24. Existing conditions and alternative C calculated variables

Approach Location	S_{ra}	S_{ri}	t_{Ga}	t_{Gi}	N_a
Rte 35 SE NWB	8	8	1.500	1.500	2
Rte 35 NW SEB	8	8	1.125	1.125	2
Rte 66 EB	24	24	1.125	1.125	2
Asbury Ave WB	24	24	1.500	1.500	1
Rte 66 EB at Inner Circle/ Robyn Rd	24	24	2.250	2.250	2
Asbury Ave WB at Inner Circle	24	24	2.250	2.250	2
East Circle approach from Rte 66	-8	-8	0.750	0.750	2
West Circle approach from Asbury Ave	-8	-8	0.750	0.750	2

Table 25 presents the accident rates for the Existing Condition and proposed Alternative C.

Table 25. Estimated accident rates based on Arndt equations

Approach Location	Existing*	Alt C	% Change	Existing*	Alt C	% Change
OUTER CIRCLE						
	Entering/Circulating			Single Vehicle		
Rte 35 SE NWB	0.060	0.060	0.0%	0.100	0.100	0.0%
Rte 35 NW SEB	0.083	0.083	0.0%	0.021	0.021	0.0%
Rte 66 EB	0.379	0.379	0.0%	0.000	0.000	0.0%
Asbury Ave WB	0.316	0.316	0.0%	0.026	0.026	0.0%
Rte 66/35 to Asbury Ave**	n/a	0.044	74.1%	n/a	0.001	
Asbury Ave to Rte 35***	n/a	0.069	73.3%	n/a	0.001	98.2%
	Approach-RearEnd			Other		
Rte 35 SE NWB	0.013	0.013	0.0%	0.035	0.035	0.0%
Rte 35 NW SEB	0.074	0.074	0.0%	0.055	0.055	0.0%
Rte 66 EB	0.415	0.415	0.0%	0.065	0.065	0.0%
Asbury Ave WB	0.028	0.028	0.0%	0.051	0.051	0.0%
Rte 66/35 to Asbury Ave**	n/a	0.031	18.4%	n/a	0.083	14.4%
Asbury Ave to Rte 35***	n/a	0.061	7.6%	n/a	0.077	6.1%
	Exiting/Circulating			Sideswipe		
Rte 35 SE NWB	0.001	0.001	0.0%	0.018	0.018	0.0%
Rte 35 NW SEB	0.001	0.001	0.0%	0.027	0.027	0.0%
Rte 66 EB	0.077	0.077	0.0%	0.027	0.027	0.0%
Asbury Ave WB	0.055	0.055	0.0%	0.022	0.022	0.0%
Rte 66/35 to Asbury Ave**	n/a	0.001	98.1%	n/a	0.007	12.5%
Asbury Ave to Rte 35***	n/a	0.001	98.7%	n/a	0.016	5.9%
INNER CIRCLE						
	Entering/Circ			Single Vehicle		
Rte 66 EB at Inner Circle/ Robyn Rd	0.170	n/a		0.000	n/a	
Asbury Ave WB at Inner Circle	0.258	n/a		0.055	n/a	
	Approach-Rear-End			Other		
Rte 66 EB at Inner Circle/ Robyn Rd	0.038	n/a		0.097	n/a	
Asbury Ave WB at Inner Circle	0.066	n/a		0.082	n/a	
	Exiting/Circulating			Sideswipe		
Rte 66 EB at Inner Circle/ Robyn Rd	0.052	n/a		0.008	n/a	
Asbury Ave WB at Inner Circle	0.075	n/a		0.017	n/a	

* Existing and all alternatives based on AADTs generated from the OD Tables.
** New link creating west circle
*** New link creating east circle
n/a = not applicable because the intersection does not exist for this alternative
0.xxx (green) = lower (better) accident rates predicted
0.xxx (red) = higher (worse) accident rates predicted
(blue boxes with arrow) = corresponding approaches between alternatives

The greatest improvement in the facility was seen for the exiting/circulating accident rate on the Asbury Avenue to Route 35 eastbound link that corresponds with the decrease in both circulating and exiting traffic volumes at this location. Significant decreases were also observed here for the entering/circulating accident type with the replacement of the tight inner circle with the two larger circles and a decrease in the approach traffic volumes.

Table 26. Percent difference in accident rates between alternatives

	Model Used/ Percent Change	
Accident Type	**Maycock & Hall**	**Arndt**
Entering/Circ*	-27.7%	24.9%
Approach-Rear-End	18.6%	1.9%
Single Vehicle	14.0%	26.2%
Other	1.3%	4.9%
Exiting/Circulating	n/a	47.9%
Sideswipe	n/a	1.7%
Total Percent Change	***13.3%***	***18.3%***

0.xxx = lower (better) accident rates predicted (green)
0.xxx = higher (worse) accident rates predicted (red)
* Entering/Circulating accident rates could not be computed for the Existing Conditions for the inner circle approaches due to the inability for the Maycock & Hall equations to handle the nonstandard angles, hence this figure (-27.7%) does not represent the actual percent change in the accident rate because two calculations are incomplete.

Finally, Table 26 gives the reader a summary of the empirical analysis results. Based on these results, Alternative C proves to be a safer alternative than the current traffic circle design for all accident types. Therefore, it is anticipated that providing drivers with more storage space within the facility for the key movements that previously used the inner circle is a good safety decision with a predicted reduction in the annual accident rate of approximately 15.8 percent, should the traffic volumes and patterns remain constant from year to year.

Modeling the Treatments for Simulation

The safety treatment options discussed above are easily modeled using the PARAMICS computer software package. However, care is needed. PARAMICS has limitations in modeling the effects of certain geometric parameters. For example, consider a situation where the roadway width is altered or superelevation imposed on the circulating roadway in a traffic circle. In the real world environment, these treatments would both have a significant impact on speeds in the facility. However, PARAMICS does not respond to these changes in geometry. What PARAMICS does allow the user to do is input a given percent speed reduction that would be anticipated due to the presence of a curve. Therefore, when modeling the treatments above, a percent speed reduction must be entered to reflect the impacts of making such a change. For further discussion on implementing scenarios in PARAMICS, see Project Analysis Background, page 68.

The existing conditions and two improvement scenarios were developed for the Asbury Park traffic circle. The scenarios that were developed are:

- "Case 1" – Existing Conditions,
- "Case 2" – (Alternative C) Remove the inner circle and add new links on each end to create two "mini" traffic circles. This alternative also has enhancements such as geometry, lighting and signage changes, and
- "Case 3" – (Alternative C with yields on approaches) Case 2 plus moving all the yields to the approaches.

The geometry for Cases 2 and 3 can be seen in Figure 30. It is apparent that the inner circle has been eliminated and two separate circles have been created. The purpose of removing the inner circle was to spread out the conflict points associated with the inner circle. Also, in Cases 2 and 3 enhancements such as approach geometry, lane widths, signage and lighting were introduced.

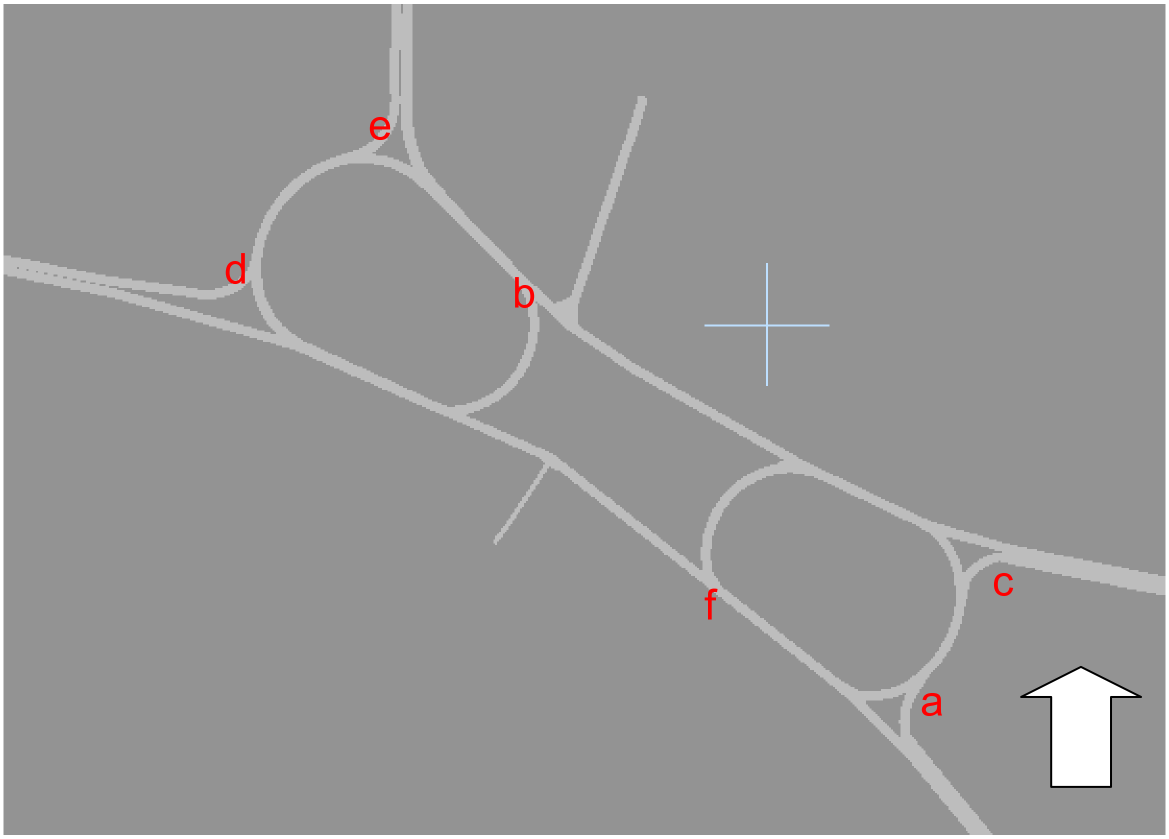


Figure 54. Geometry for cases 2 and 3

Case 3 aims to maintain uniform speeds within the circles by building on Case 2. To accomplish this, the yield control was moved onto each of the approaches. This makes it possible for the circulating traffic to have the right-of-way and continue around the facility with minimal conflicts. The traffic on the two new links must yield to the Route 35 traffic.

Location a: Route 35 Northbound Approach

Presently, at the Route 35 northbound approach the right-of-way is given to the approaching traffic. This requires the circulating vehicles to yield, therefore slowing them down as evident by the high peak at about the 6 mph mark in Figure 55. When traffic volumes are high, the queue may extend far enough to where it will block Route 35 southbound exiting traffic. Figure 55 shows the existing speed distribution at this location. It is apparent that the approaching speeds on Route 35 are much greater than the circulating speeds. Ideally, when traffic volumes are light the approaching and circulating speeds will be identical. This means the yielding traffic is able to enter the facility without slowing down the conflicting traffic. If there is a large difference, this may lead to rear-end collisions. When volumes are higher it is necessary for the yielding traffic to slow down much more. Therefore, the traffic with the right-of-way is expected to maintain the same speed while the yielding traffic will be traveling much slower.

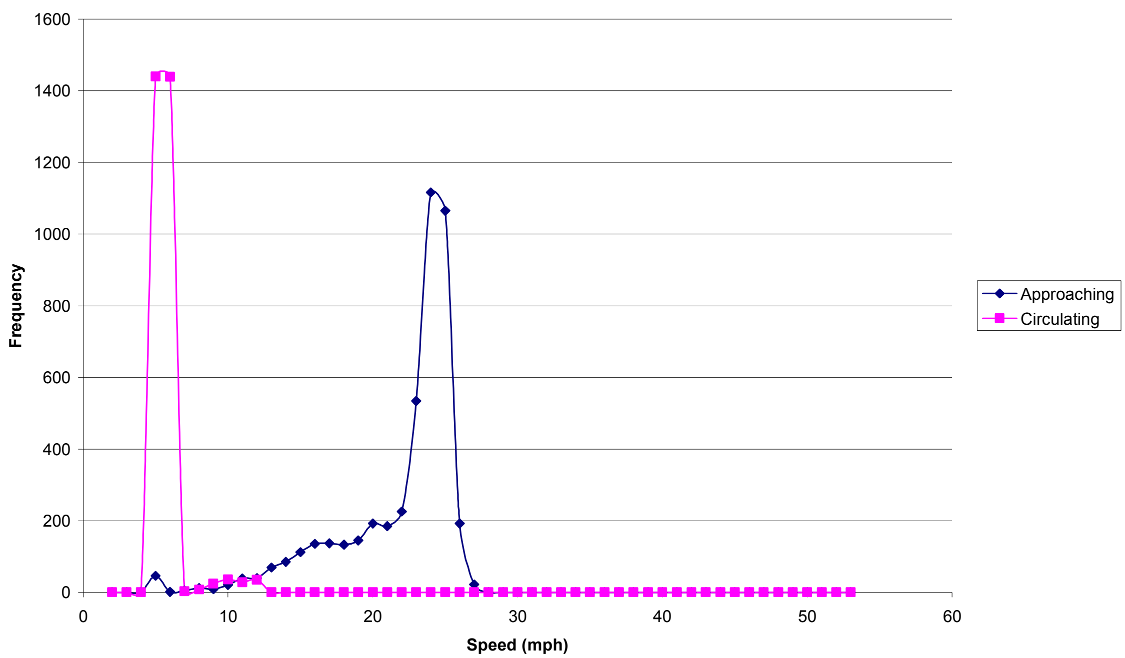


Figure 55. Rt. 35 NB speeds, existing condition, AM Peak – Case 1

Case 2 introduced geometric enhancements to the approach including increasing the curvature on the approach leg to reduce speeds. As Figure 56 indicates the circulating speeds now only have peak at 5 mph. The major change is the reduction of approaching speeds, by approximately 10 mph from 22 mph to 12 mph.

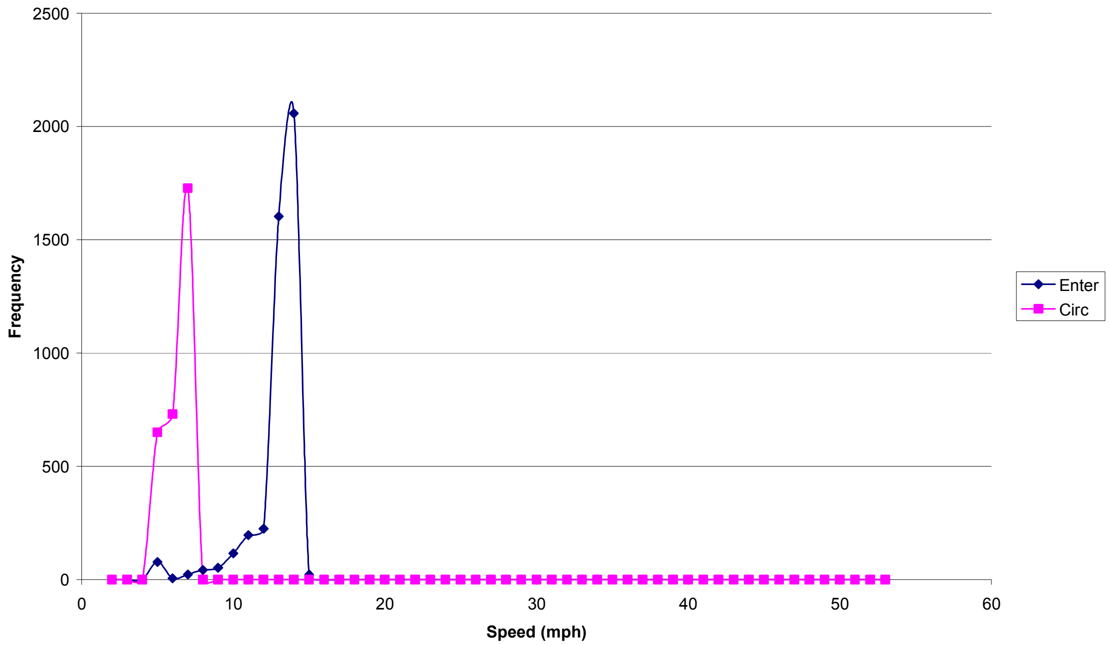


Figure 56. Rt. 35 NB speed distributions, alternative C, AM peak – Case 2

By changing the location of the yield control as Case 3 does, the speed characteristics are much different. Figure 57 shows this change for the AM peak. The approaching speeds are nearly 5 mph, while the circulating speeds are between 20 and 25 mph. The results are similar for the PM peak (not shown).

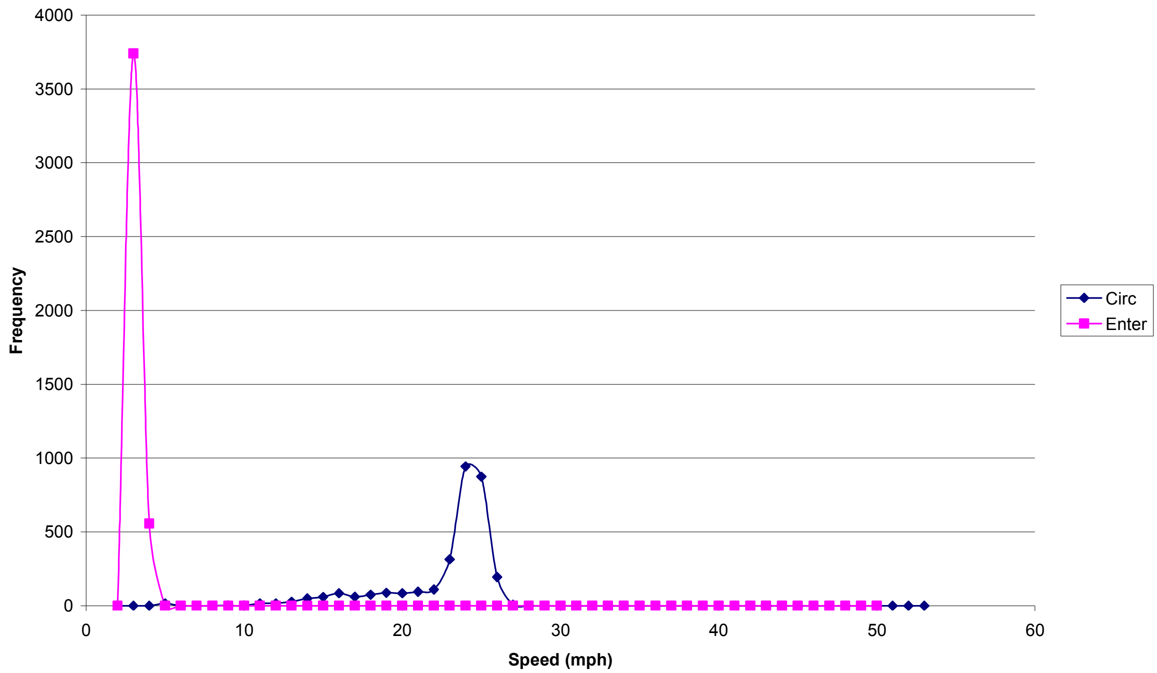


Figure 57. Rt. 35 NB speed distributions, alternative C, AM peak – Case 3

Location b: Route 35 Northbound (at north side of inner circle)

This location is where the inner circle intersects with Route 35 northbound. Due to the tight geometry of the inner circle and the high speeds on the outer circle there are frequently accidents at this location. Figure 58 shows the existing speed distributions at this location. There are several movements shown in this figure, first is the traffic within the inner circle approaching Route 35 north, second is the traffic traveling on Route 35 north and lastly there is the traffic exiting Route 35 north to the inner circle. The speed distribution clearly shows high degrees of variation between the movements. The approaching speeds from the inner circle range from 5 to 15 mph while the Route 35 northbound traffic ranges from 20 to 40 mph. The vehicles traveling on Route 35 north and exiting onto the inner circle are typically traveling at speeds around 25 mph. The large variation in speeds is a main factor in the high accident rate at this location.

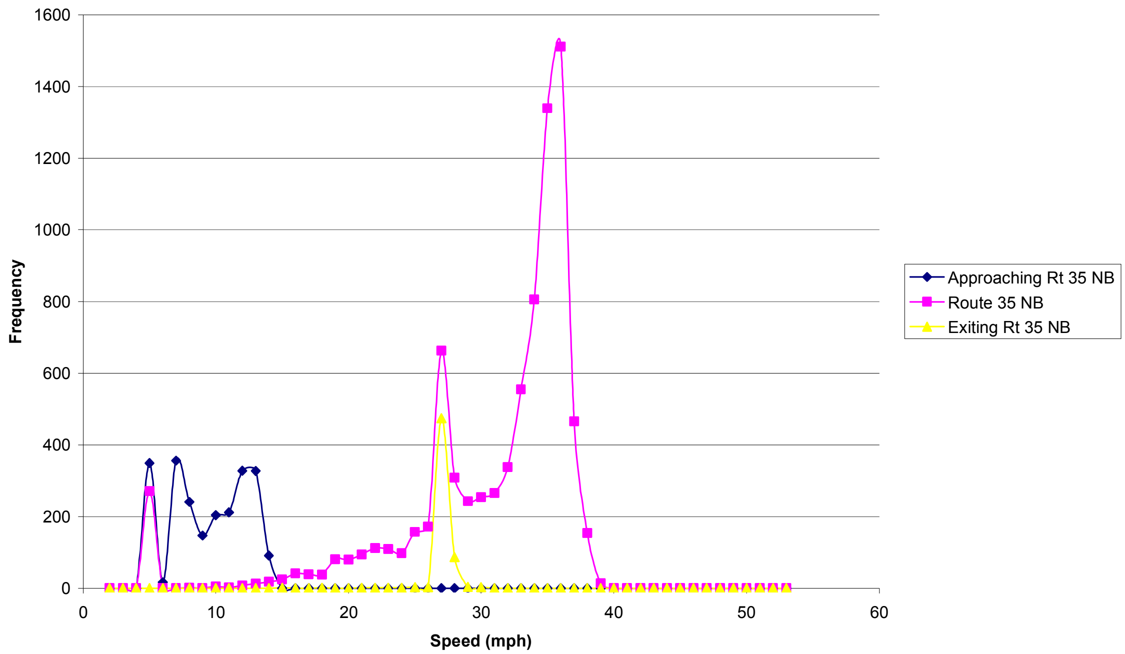


Figure 58. Rt. 35 NB inner circle speeds, existing condition, AM peak – Case 1

Case 2 eliminates the inner circle and replaces it with new links carefully constructed to maintain consistent speeds and add more storage capacity. The new links as shown in Figure 30 have a similar curvature as the ends of the outer circle; this is to create the feeling of two separate circles instead of one large facility. In this case, the merge point with Route 35 northbound on the northern circle is being compared to the same merge point with the inner circle. The yield for both Cases 2 and 3 is located on the circulating link (not Route 35 north). This being the case, the speed distributions are very similar for the two cases. For illustrative purposes the distribution for AM peak for Case 3 is shown in Figure 59.

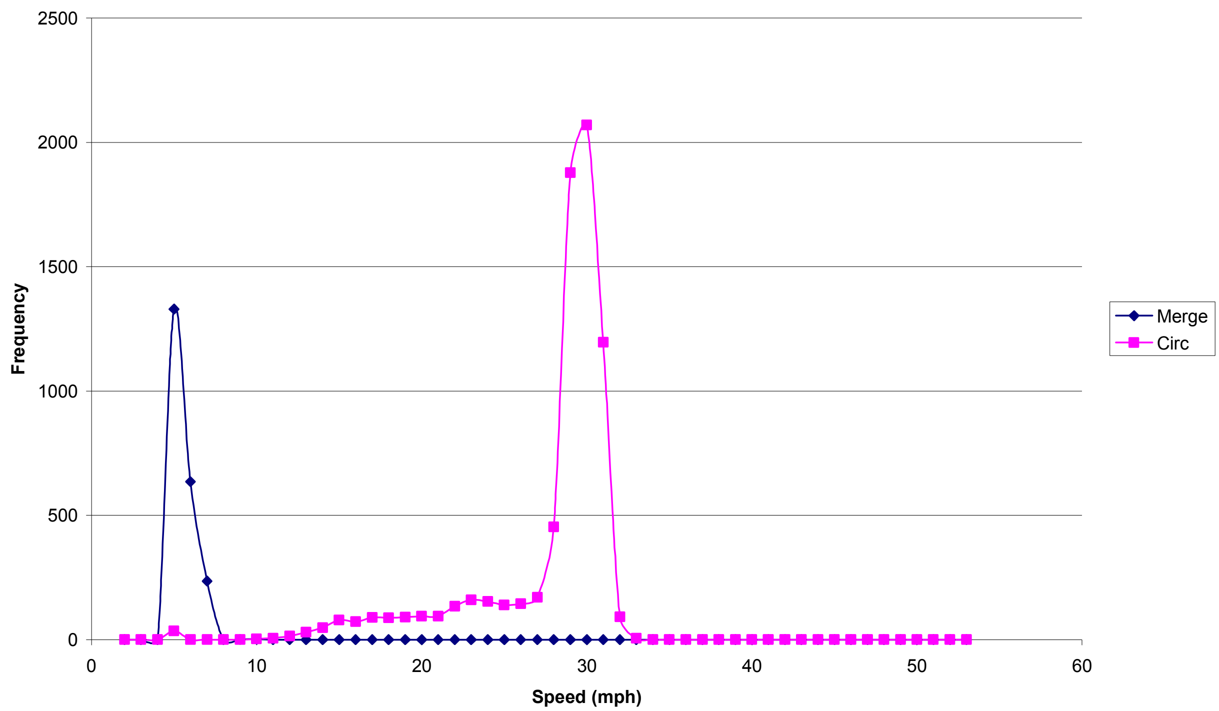


Figure 59. Rt. 35 NB at new merge point, AM peak, alternative C – Case 3

Comparing Figure 58 with Figure 59 it is evident that removing the inner circle has value. There is much less speed variation for each movement. The northbound (circulating) traffic tends to be traveling at 30 mph, while the merging traffic on the new link is yielding, therefore, their speeds are approximately 5 mph.

Location c: Route 16 Westbound Approach and Route 35 Northbound

This location is where Route 16 westbound intersects with the Route 35 northbound circulating traffic. Route 16 vehicles currently have the right-of-way and the speed limit on that road is 35 mph. This means the traffic entering the circle will be traveling at that speed. The geometry entering from Route 16 is fairly straight, therefore little is done geometrically to slow down vehicles.

The speed distribution for the existing conditions can be seen in Figure 60. The circulating traffic tends to be slowed to 5 – 10 mph, while the entering traffic reaches 35 mph. Ideally, the circulating speed would be increased and the approaching speed would be decreased so that they were approximately the same speed. The next best situation would be a higher speed for circulating traffic than approaching traffic with a yield sign on the approach and not in the circle.

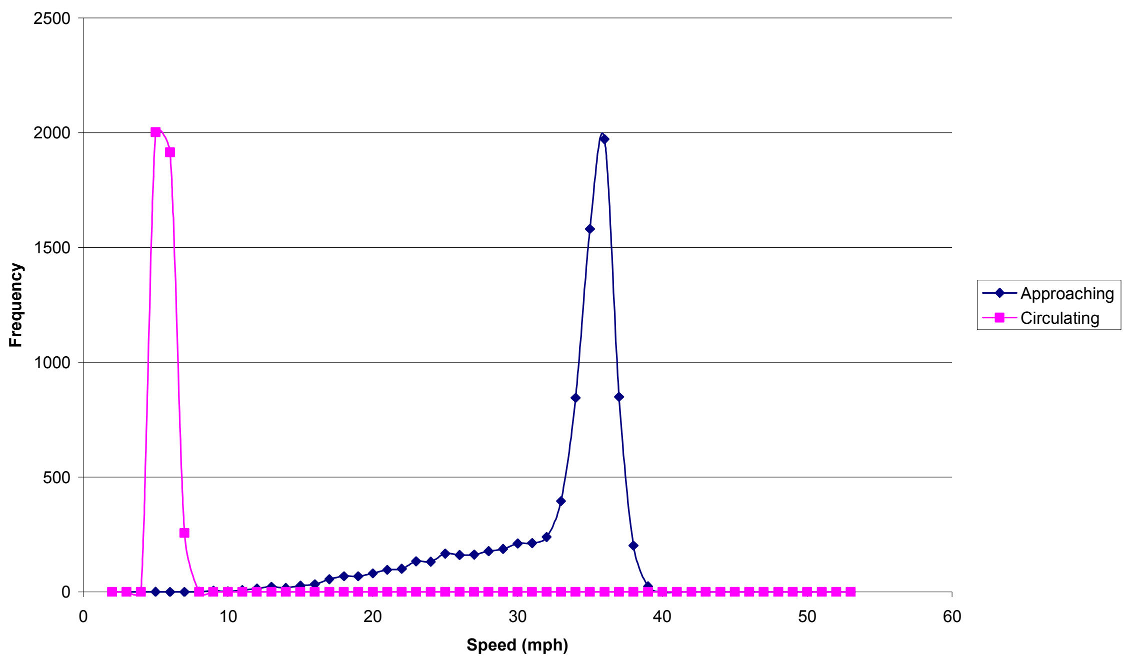


Figure 60. Rt. 16 WB approach speeds, AM peak, existing condition – Case 1

Since Route 16 has a relatively low speed limit, major changes were not necessary to this approach. However, it was necessary to slightly reconfigure the approach geometry and also introduce appropriate signage and lighting.

Figure 61 shows the speed distribution for Case 2.

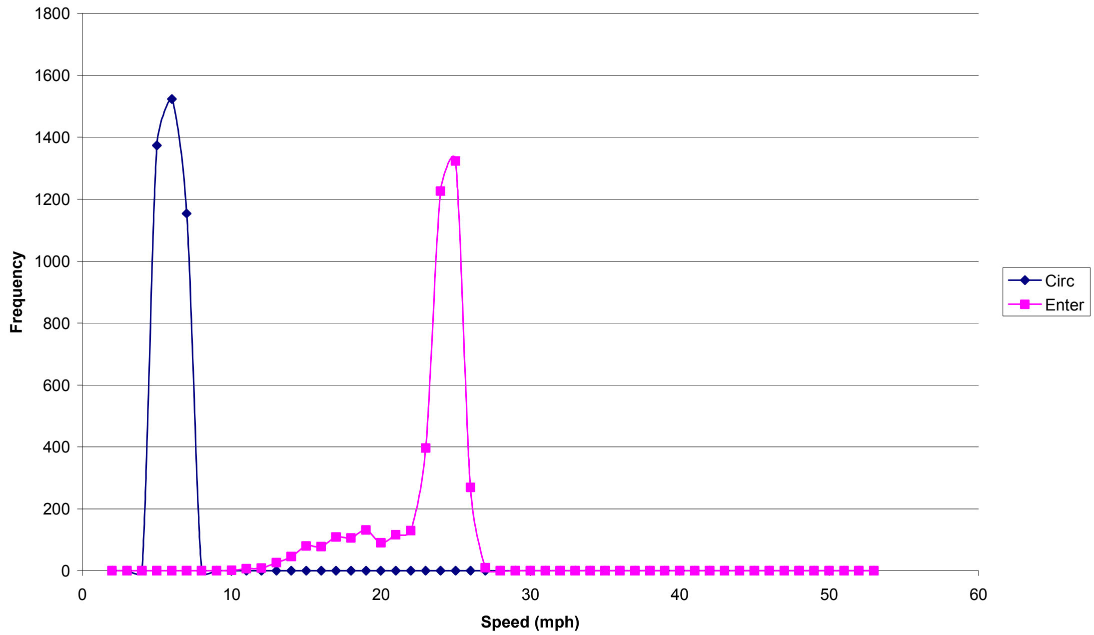


Figure 61. Rt. 16 WB approach speeds, AM peak, alternative C – Case 2

As a result of the slight changes in Case 2, the approaching and circulating speeds were more closely aligned. The circulating speeds remained the same but the approaching speeds were reduced by approximately 10 mph.

Next, by moving the yield to the approach as in Case 3, there is a significant change in the way the vehicles move through the facility. Figure 62 illustrates this change. The plot is almost the reverse of the one from Case 1. The circulating traffic is now predominantly traveling at 20 mph, while the Route 16 traffic is now slowed to 5 mph.

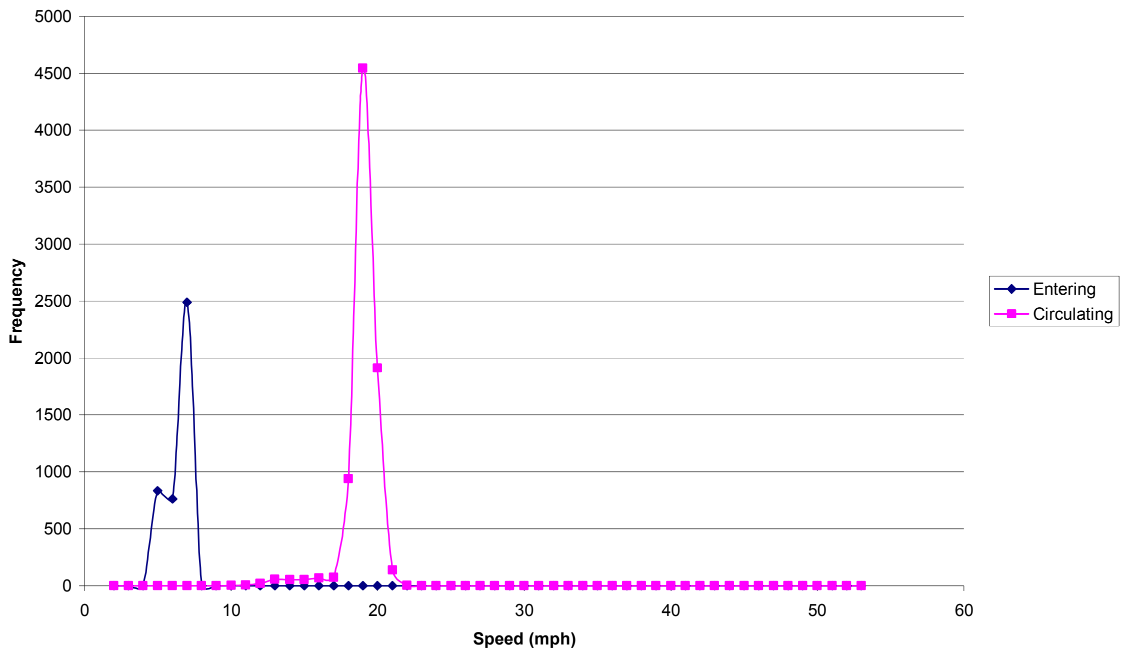


Figure 62. Rt. 16 WB approach speeds, AM peak, alternative C– Case 3

Location d: Route 66 Eastbound Approach and Route 35 Southbound

Based on the accident analysis there is a large number of accidents at this location. Most of them are rear-end collisions at the approach on Route 35 south. The traffic entering the circle from Route 66 currently has the right-of-way. The approach for Route 66 is virtually a straight line tangent to the circle, therefore, high speeds are often seen at this location. A speed distribution for the existing conditions can be seen in Figure 63.

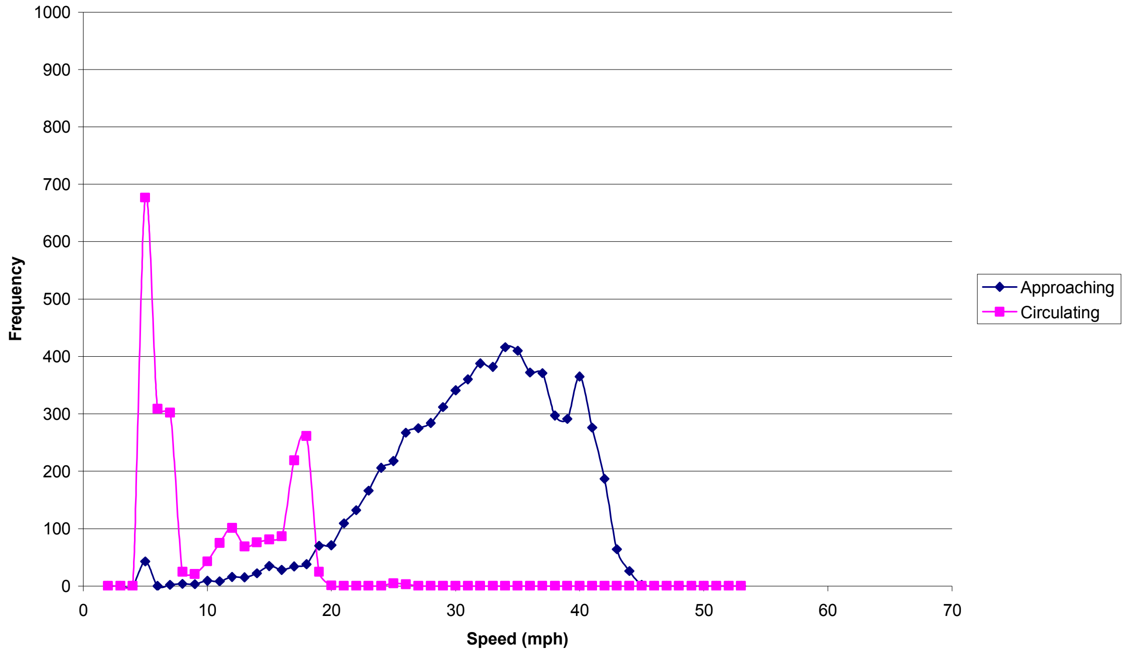


Figure 63. Rt. 66 EB approach speeds, AM peak, existing condition – Case 1

The vehicles entering the traffic circle from Route 66 tend to do so between 20 and 45 mph. The circulating traffic tends to be traveling at two distinct speeds, 5 and 18 mph. There is presently little uniformity amongst the speeds at this location.

Case 2 (not shown) enhances the geometry to reduce the entry curvature, therefore, reducing the speed to approximately 30 mph with little variation. The circulating speeds are much more uniform. These speeds are all less than 10 mph. The reason for this is that all of the vehicles are yielding on the circulating roadway.

Case 3 radically changes how this facility operates, as seen in Figure 64. The circulating speeds are now predominantly around 20 mph while the Route 66 eastbound speeds are slowed to 5 mph with the yield. This allows the circulating traffic to freely move without interruption. It should be noted that the main approach at this location, Route 66, has the yield control in this case. Although the plot clearly shows that the large amount of traffic is coming from this approach it was necessary to give the circulating roadway the right-of-way in this case. It would not be logical to move the yields to the approaches in all but one of the locations. Moving the yield to this location does add value for the circle. As Figure 63 clearly shows the approaching speeds reach 45 mph as vehicles entered the facility. In this case the vehicles must slow down, therefore, reducing the speed within the circle. Moving the yields to the approaches guarantees the traffic circle will not deadlock.

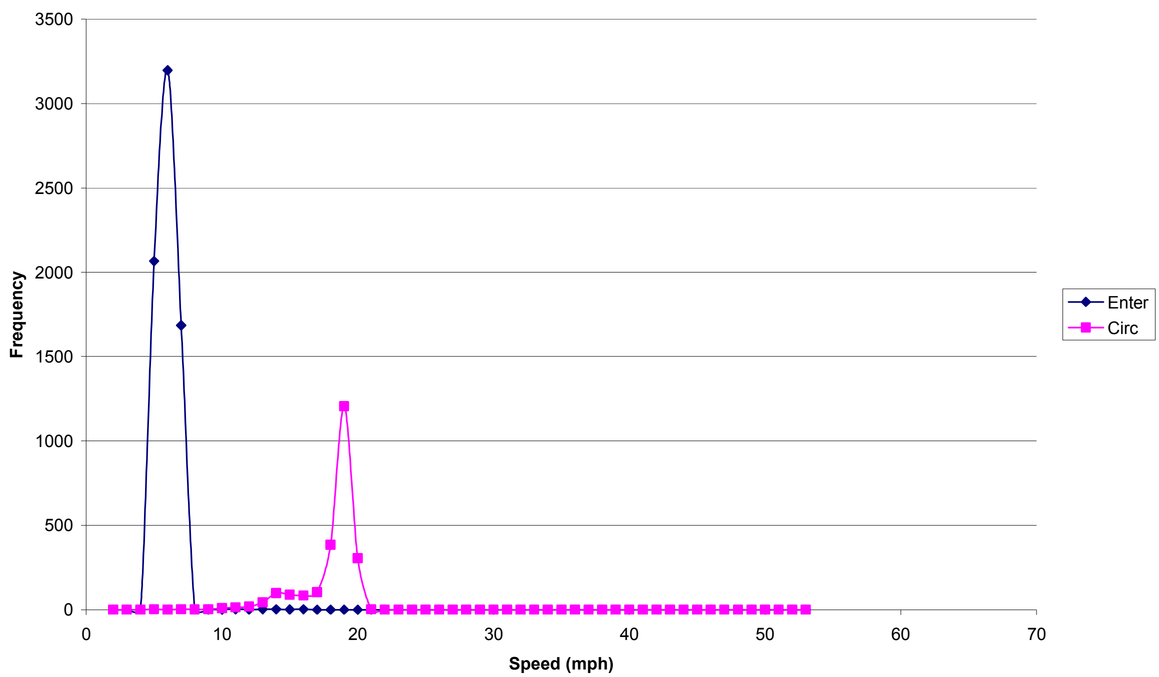


Figure 64. Rt. 66 EB approach speeds, AM peak, alternative C– Case 3

Location e: Route 35 Southbound Approach

Like the other locations within this traffic circle the yield control is on the circulating roadway. The speed distribution for the existing conditions can be seen in Figure 65. The approaching speeds are generally 30 mph while the circulating speeds have a great deal of variation, with two main peaks at 5 and 18 mph.

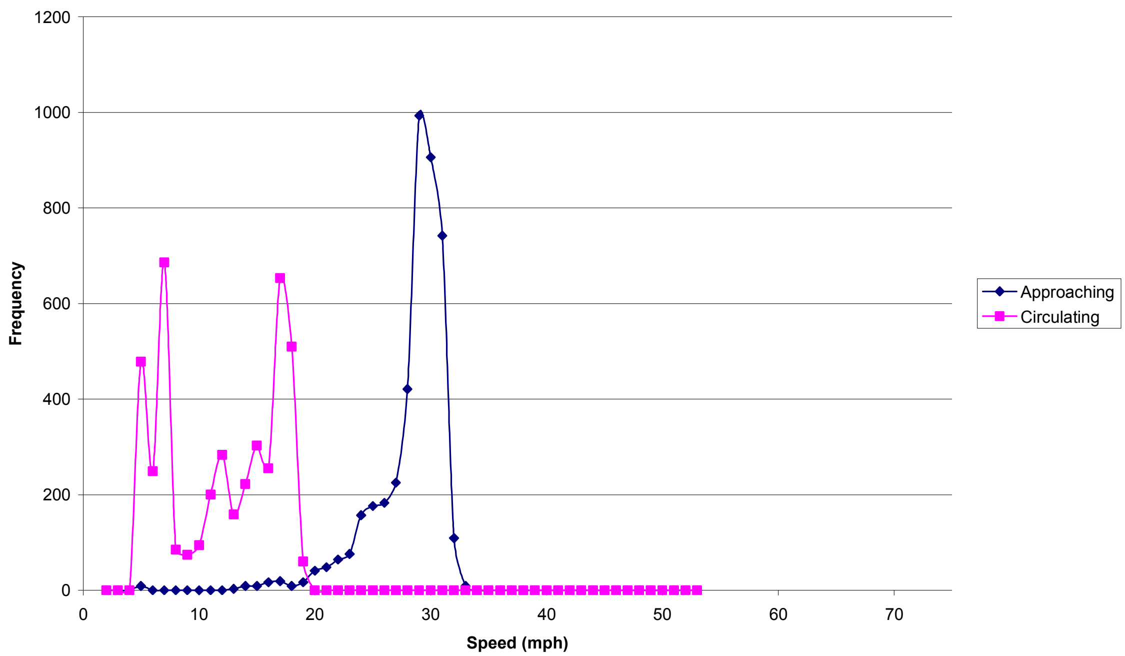


Figure 65. Rt. 35 SB approach speeds, AM peak, existing condition – Case 1

In Case 2, the approaching speeds are reduced by introducing geometric enhancements. As Figure 66 shows both the circulating and entering speeds are reduced. There is a significant reduction in the variation of the circulating speeds. The approaching speeds are also reduced by approximately 15 mph. This reduction was due mainly to geometric changes to the approach.

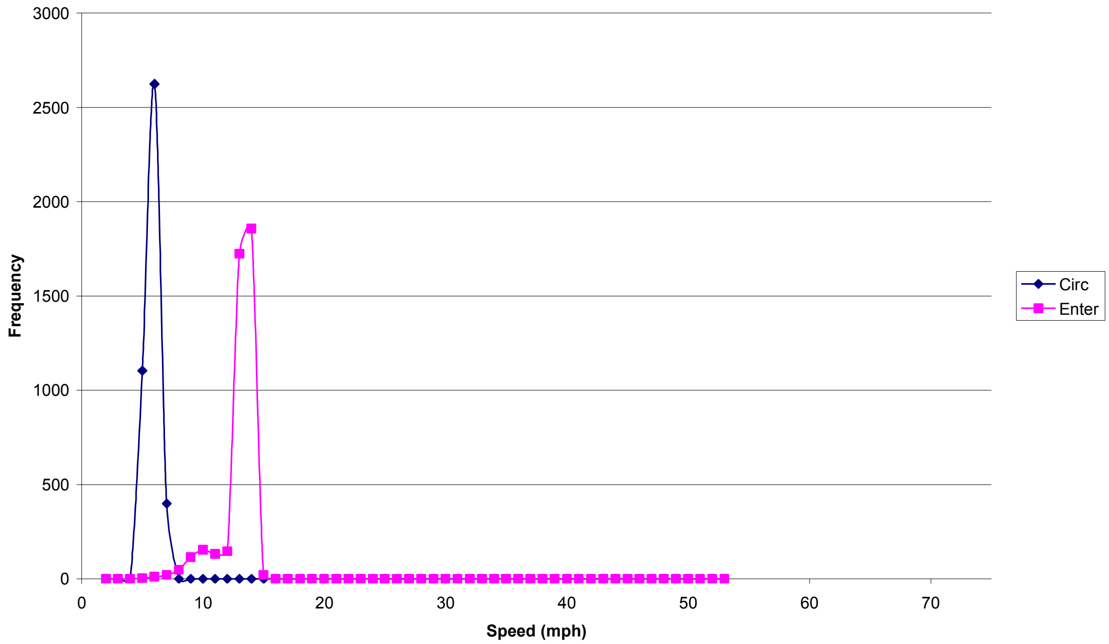


Figure 66. Rt. 35 SB approach speeds, alternative C, AM peak – Case 2

Case 3, further enhances this location. This case changes the location of the yield from the circulating roadway to the approach. Figure 67 shows the speed distribution after this change. The approaching speeds have a sharp peak at 5 mph while the circulating speeds have a sharp peak at 30 mph.

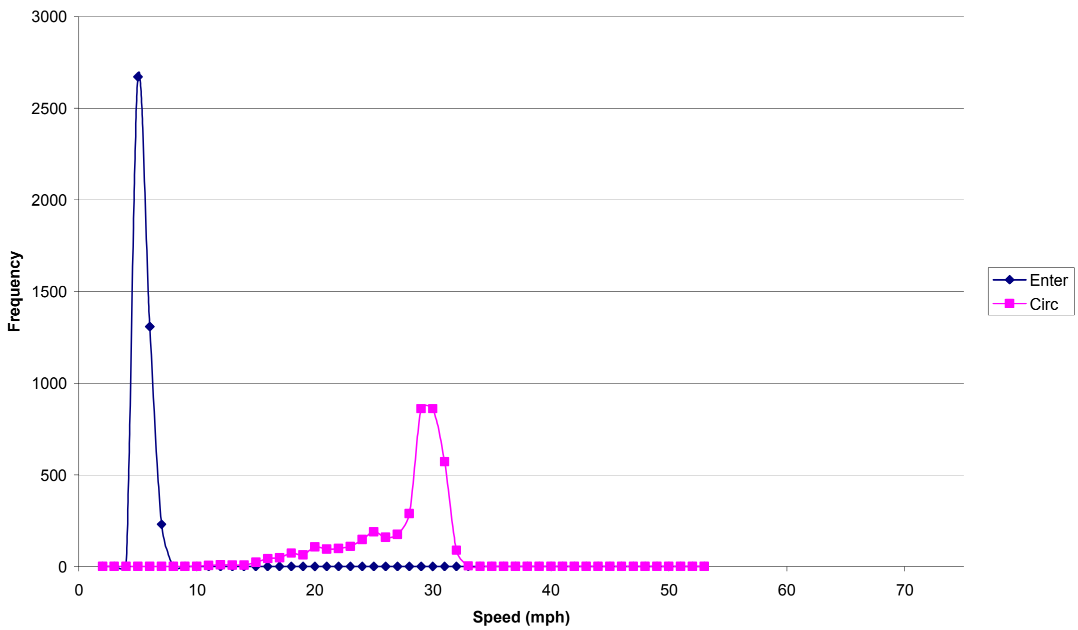


Figure 67. Rt. 35 SB approach speeds, AM peak, alternative C– Case 3

Location f: Route 35 Southbound (at south side of inner circle)

This location is where the inner circle intersects with Route 35 southbound. Due to the tight geometry of the inner circle, high speeds on the outer circle, and the proximity of commercial driveway cuts, accidents are frequent at this location. Figure 68 shows the existing speed distributions at this location. There are several movements shown in this figure, first is the traffic within the inner circle approaching Route 35 south, second is the traffic traveling on Route 35 south and lastly there is the traffic exiting Route 35 south to enter the inner circle. The speed distribution clearly shows high degrees of variation between the movements. The approaching speed from the inner circle is 5 mph; the Route 35 southbound traffic speeds are as high as 35 mph. The vehicles traveling on Route 35 south and exiting into the inner circle are typically traveling at speeds around 10 to 15 mph. The large variation in speeds is a main factor in the high accident rate at this location.

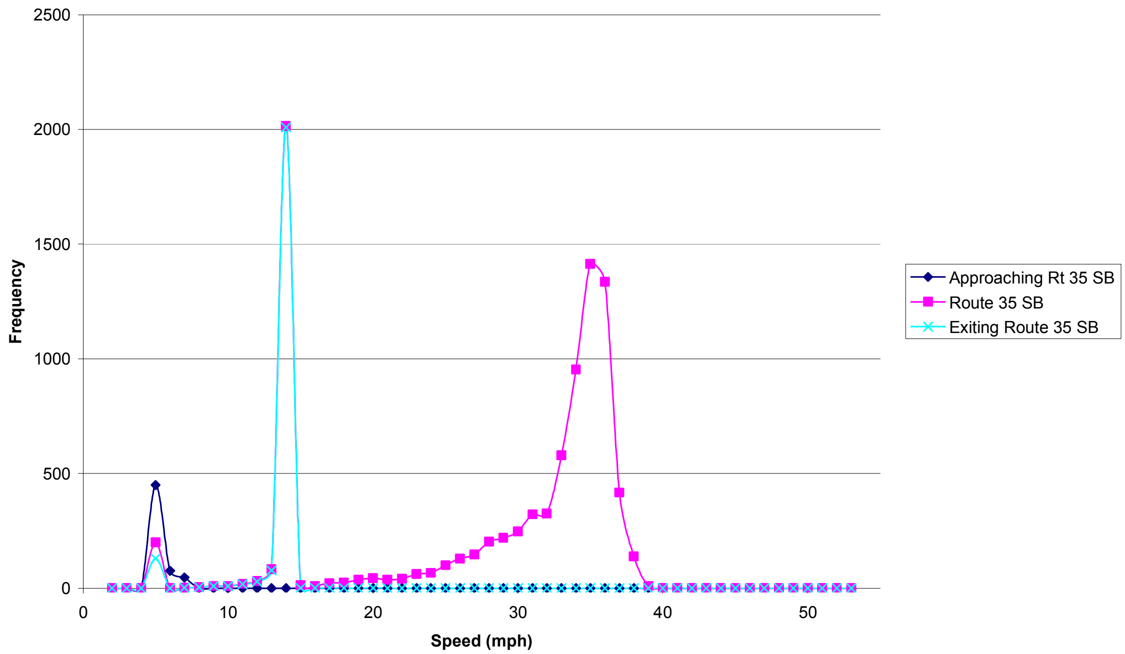


Figure 68. Rt. 35 SB inner circle speeds, AM peak, existing condition–Case 1

Case 2 eliminates the inner circle and replaces it with new links carefully constructed. The new links (as shown in Figure 30) have similar curvature as the ends of the large circle. This is to create the feeling of two separate circles instead of one large facility. In this case, the merge point with Route 35 southbound on the southern circle is being compared to the same merge point with the inner circle. The yield for both Cases 2 and 3 is located on the circulating link (not Route 35 south). This being the case, the speed distributions are similar. For illustrative purposes the distribution for AM peak for Case 3 is shown in Figure 69.

Comparing Figure 68 and Figure 69 it is evident that removing the inner circle has value. The speeds for the individual movements are more uniform with themselves although the two movements have significantly different peak speeds. The southbound traffic tends to be traveling at 30 mph, while the merging traffic peaks at 5 mph.

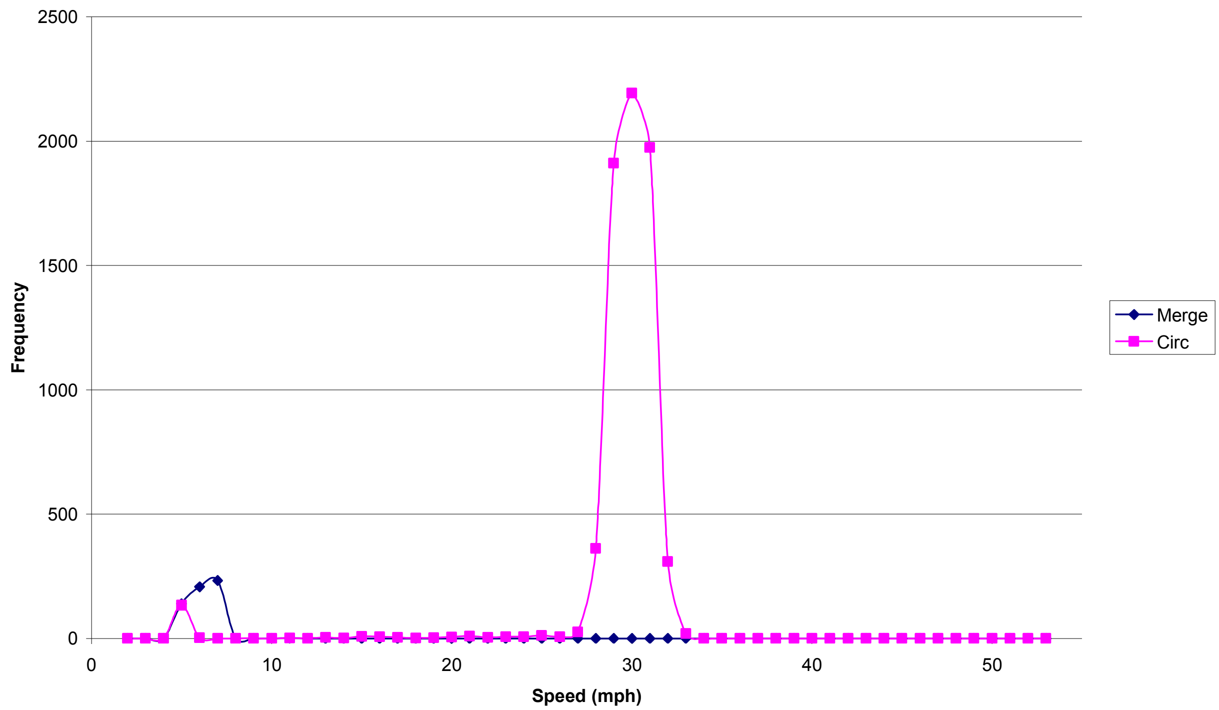


Figure 69. Rt. 35 SB new merge point speeds, AM peak, alt C– Case 3

Vehicle Trajectories Through the Traffic Circle

It is also important to look at changes in speeds as vehicles travel through the facility. Therefore, speed trajectories were examined for each origin-destination pair in the traffic circle to look at how vehicles travel through the circle. These plots through the traffic circle show the speed of each simulated vehicle as it travels from one location to another. These locations are zones located on the extents of the circle, therefore, the plots do not show movements only in the circle.

The example shown below is for vehicles going from the northbound entrance on Route 35 to the eastbound exit on Route 66. Figure 70 below shows the speed trajectory of vehicles making this movement in Case 1 under existing conditions.

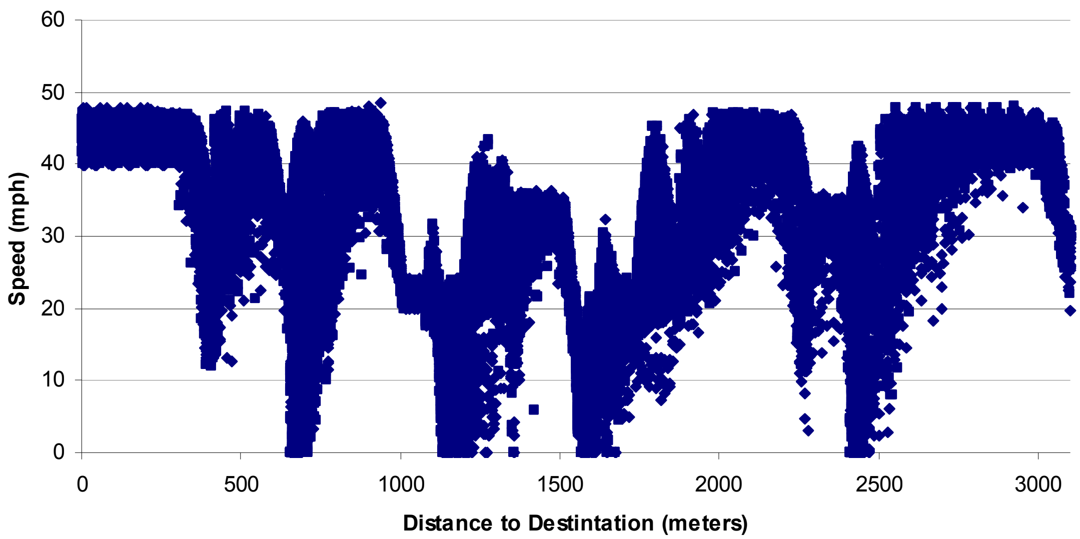


Figure 70. Speed trajectory, Rt. 35 north to Rt. 66 east of the circle – Case 1

The x-axis is labeled as “Distance to Destination” therefore, the vehicle path is from right to left. In other words, the vehicles start on the right side of the plot at the maximum distance, their destination is at zero meters. The section of the plot that pertains to the circle is from 1740 m (Route 35 north approach) to 1050 m (Route 66 diverge) on the “Distance to Destination” scale. The scatter to either side of that is the remaining network both upstream and downstream of the circle. As indicated by the graph, the approaching speed on Route 35 varies between 5 to 30 MPH. The high speeds are associated with the approaching vehicles having the right-of-way on this approach. The merge point with the center circle (location b) is at 1350 m. The speeds between the approach and this location are predominately between 0 and 40 mph. The reason for the low speeds is due to having the yield within the circulating roadway, this prohibits vehicles from maintaining a uniform speed through the circle. It should also be noted that a large variation exists at the merge point with the inner circle. The remained of the trajectory when the vehicle is within the circle has varying speeds between 0 and 40 mph. The high speeds are associated with vehicles passing the yield at location e unimpeded but are forced to slow down slightly after due to backups at the Route 35 southbound junction with Route 66. Although the vehicles in this plot are diverging prior to this point they are entering the back of queue in some instances.

Case 2 produces similar but cleaner results as shown in Figure 67. The circle is still located between 1740 m and 1050 m. The major change is that the new diverge point at the inner circle is at 1475 m (location b). The speed distribution between the start of the circle and this point is much more consistent. The speeds at the new location range between 30 and 35 mph. Once the vehicles pass this new point they have speeds predominantly between 0 and 30 mph. The slower speeds are still due to the need for the vehicles to yield within the traffic circle.

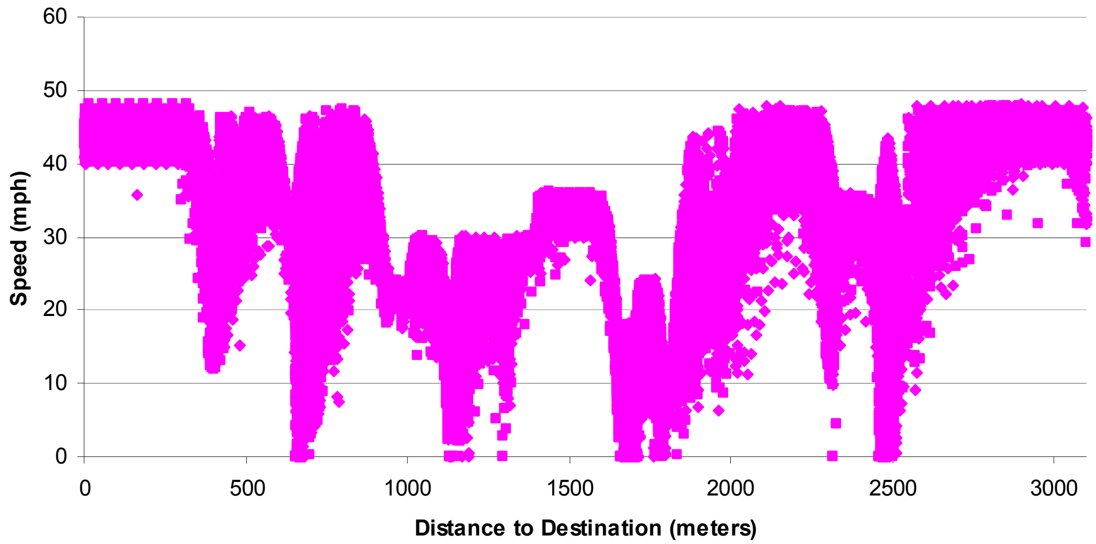


Figure 71. Speed trajectory, Rt. 35 north to Rt. 66 east of the circle – Case 2

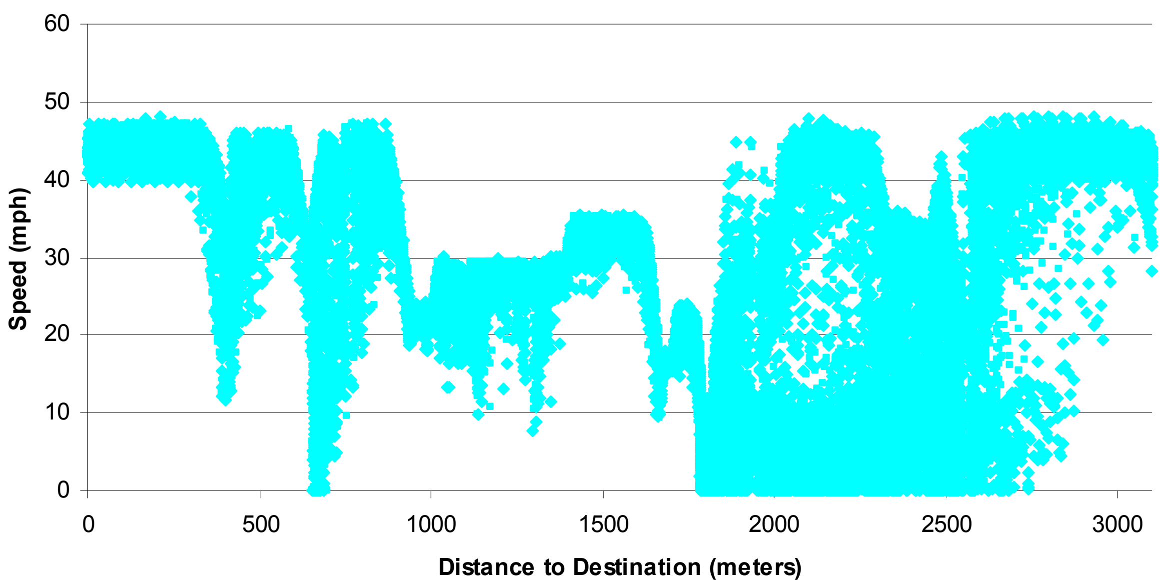


Figure 72. Speed trajectory, Rt. 35 north to Rt. 66 east of the circle – Case 3

Case 3 produces the results shown in Figure 72. The significant change is that the approaching speeds are primarily slower. The reason for this is that the yield is on the approach in this case. The speeds within the circle however, comprise a much tighter band. This is due to the fact that the vehicles are not forced to yield at each conflict point. It should be noted that the large amount of scatter that appears to be occurring on Route 35 prior to entering the circle is due to PARAMICS modeling sensitivities. When a yield is introduced in PARAMICS the vehicle is forced to slow to a near stop before proceeding, regardless of what the actual conditions may be. Therefore, this is causing the intersections on Route 35 prior to entering the circle to backup. With these issues known, it is possible for future runs to be calibrated to allow for higher speeds at the yield control.

To ensure that the issues described above were really modeling sensitivities the team checked the delays and queue lengths against similar data for multi-lane roundabouts across the US. From similar facilities the team found that for comparable facilities the delays should be in the 10 to 25 second range per vehicle and that 95th percentile queue lengths should be between 0 and 7 vehicles. The only location where this does not hold true is at the Route 16 approach (location c) where the existing one-lane approach should be upgraded to a two-lane approach.

Another path through the traffic circle is from the Route 35 south approach to Route 16 west. Figure 73 shows the Case 1 vehicle trajectories for this path. The circle is located between 1820 m (Route 35 south approach) and 1360 m (Route 16 west diverge). It is evident that the speeds within the circle range between 0 and 40 mph. The low speeds are typically in the vicinity of the yield controls. The merge point with the inner circle is at 1700 m. From the approach to this point the speeds have no uniformity. From the inner circle to the Route 35 diverge at 1445 m, the speeds vary but follow a tighter pattern.

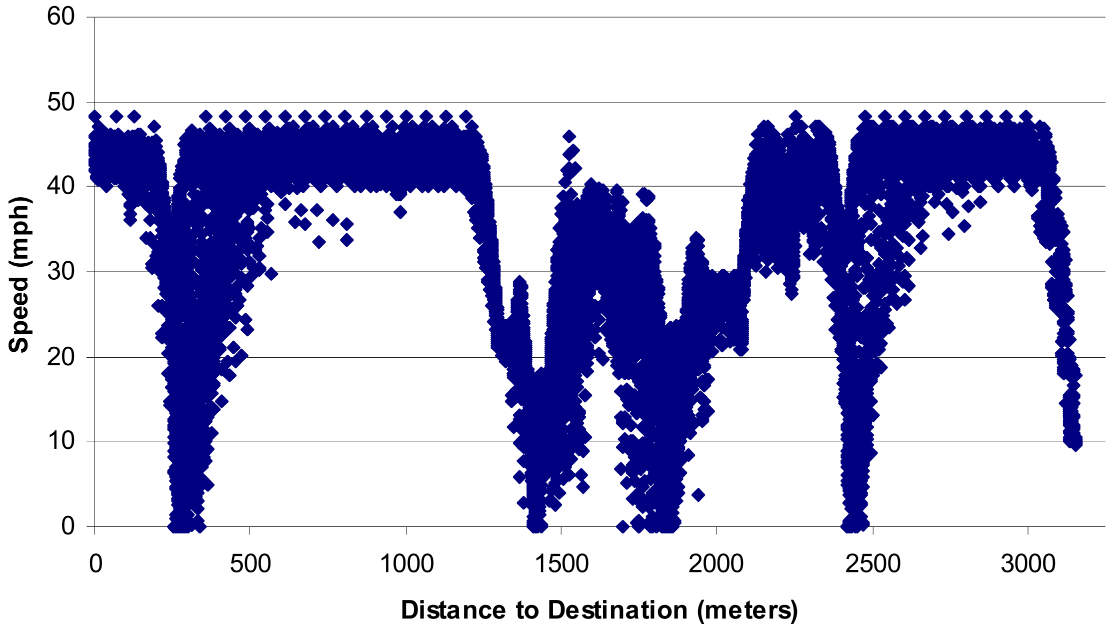


Figure 73. Speed trajectory, Rt. 35 south to Rt. 16 west of the circle – Case 1

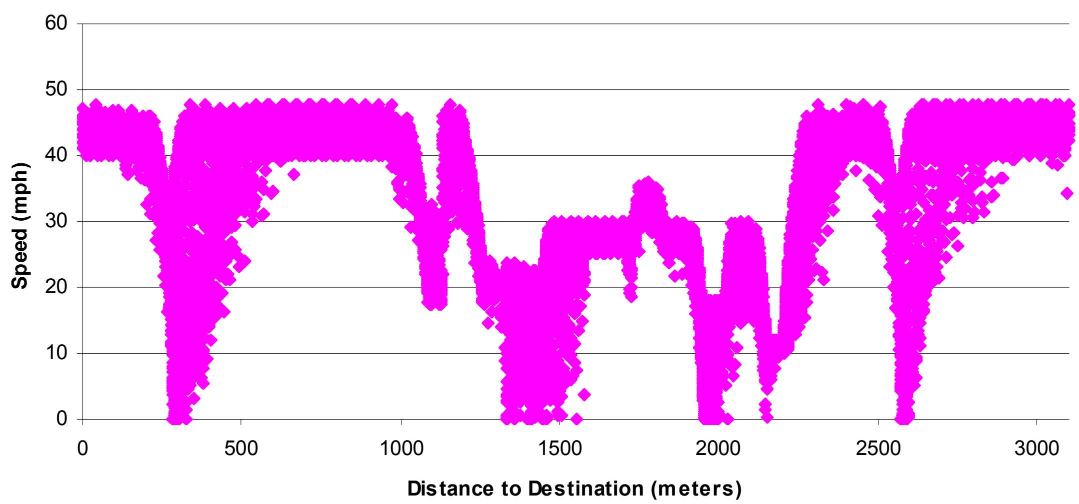


Figure 74. Speed trajectory, Rt. 35 south to Rt. 16 west of the circle – Case 2

For the same location in Case 2 there is less variation. As Figure 74 shows, the speeds are between 25 and 35 mph when vehicles initially enter. Once the vehicles reach the new diverge point (location f) the speeds reduce to 25 to 30 mph. As the vehicles continue get to the other newly constructed merge point at 1500 m the speeds start to reduce. This is due to the yield control at 1300 m (location a).

The output results for Case 3 were not as expected. The results showed that the intersections south of the traffic circle on Route 35 were backing up as far as the Route 66 approach in the circle. After carefully studying these results it was found that the problem was not with the yield controls on the approaches, rather with the PARAMICS modeling software. There are some modeling issues that prevent the vehicles from entering the circle at a yield at higher (more representable) rates of speed. This being the case, it was necessary to compare the volumes seen on these approaches with volumes of roundabouts throughout the country to ensure the traffic circle would not fail if the yields were moved to the approaches.

Asbury Park Circle Conclusions

This chapter discusses the improvements from various safety treatments for the Asbury Park traffic circle in New Jersey. The circle has been assessed using a carefully developed safety analysis methodology. Both the empirical models and traffic simulations tested support the proposition that safety will be increased with implementation of the proposed treatments.

Based on the empirical results using the Maycock and Hall equations, safety should improve at the Asbury Park traffic circle with the implementation of Alternative C.

removal of the central circle replaced by two links to create two larger circles at either end of the Asbury Park circle enabling longer queues to occur within the sub-circles while reducing the speed differential on the straight-aways and keeping this differential closer to the traffic circle approaches where speeds are typically lower.

Presently, at the Asbury Park traffic circle the speeds within the traffic circle vary greatly. These speeds are not consistent from approach to approach. These speed variations do allow for safe operation, especially for unfamiliar users. Case 2 was modeled to enhance the traffic circle while maintaining the existing yield control structure. As is mentioned in the above section, the overall patterns in Case 2 were similar to Case 1 but with much less variability. The main enhancement in this case was the removal of the inner circle. In its place two new links were added to allow for those movements. These new links created the illusion of two separate traffic circles. Other enhancements included approach geometry changes and speed limit reductions.

The reconstruction of the inner circle as done in Case 2 and 3 clearly has value in terms of safety. The weaving section is much greater as is the storage space behind the yield. To further enhance safety, the yields were moved to all of the approaches in Case 3. Although the PARAMICS software had trouble simulating the results by moving the yields to the approaches further investigation lead the team to believe that this was beneficial in terms of safety. The team checked the delays and queue lengths against similar data for multi-lane roundabouts across the US and conclude from that comparison that the delays should be in the 10 to 25 second range per vehicle and that 95th percentile queue lengths should be between 0 and 7 vehicles except at the Route 16 approach (location c) where the existing one-lane approach should be upgraded to a two-lane approach.

SAFETY ANALYSIS CONCLUSIONS

Traffic circles are insufficiently addressed through current empirical and simulation models. Thus, research about the safety and operations of these facilities need careful attention. To develop workable solutions for the three traffic circles in this study, empirical models and simulation techniques were used hand-in-hand. The empirical models chosen were from the British and Australian roundabouts literature. The simulation program selected was sensitive to lane assignment, control, and traffic volumes - three crucial elements in traffic circles operations. On the other hand, the program was insensitive to changes in superelevation, markings, directional signage, and lighting, to name but a few items. Therefore, both empirical models and simulation analyses were conducted to develop the most informed picture possible of each alternative. The results of each method are now summarized.

Summary of Empirical Analyses

Table 27. Comparison of actual and estimated annual accident rates

	Actual Annual Accident Rate	**Empirically Estimated Annual Accident Rates**	
LOCATION / Case		Maycock & Hall	Arndt
COLLINGWOOD TRAFFIC CIRCLE			
Existing Condition	30.67	5.400	2.160
Enhanced Condition		9.019	1.318
BROOKLAWN TRAFFIC CIRCLE			
Existing Condition	31.33	8.803	17.317
Alternative 2B		8.816	1.028
Alternative 2B w/ Enhancements		8.816	0.680
Alternative 2D		8.741	0.954
Alternative 2D w/ Approach Yields		8.741	0.475
ASBURY PARK TRAFFIC CIRCLE			
Existing Condition	72	26.293	3.384
Alternative C		22.790	2.453

0.xxx = lower (better) accident rates predicted
0.xxx = higher (worse) accident rates predicted

The expected number of accidents for each traffic circle's alternative designs is included in Table 27 along with the actual annual accident rates based on the data received from the NJDOT and police reports. As is clearly evident and explained previously, the empirical estimates do not equal the actual annual rates for the existing conditions (to see why, go to Review of Safety Models on page 17); however, the relative changes between alternatives is useful to observe. For example, according the both empirical models for the Asbury Park traffic circle Alternative C is an improvement over the Existing Condition (approximately 13 to 28 percent). In the case of the Collingwood traffic circle, the improvement is debatable based on the empirical results (167percent higher accident rate using Maycock & Hall, while a 39 percent lower accident rate with Arndt) so here it is crucial to examine the simulation output for further insight.

Summary of Simulation Runs

The safety treatment options discussed in each of the traffic circle sections were modeled using the PARAMICS computer software package. Table 28 shows a summary of each of the simulation runs for each of the traffic circles. It should be noted that PARAMICS has many limitations when it comes to modeling the effects of certain geometric parameters. For example, the roadway width may be altered or superelevation imposed on the circulating roadway in the traffic circle. In the real world environment, these treatments would both have a significant impact on speeds in the facility. However, PARAMICS is unable to model these effects as a direct result of changing the geometry. What PARAMICS does allow the user to do is input a given percent speed reduction that would be anticipated due to the presence of a curve. Therefore, when modeling the treatments, a percent speed reduction must be entered to reflect the impacts of making such a change.

Table 28. Comparison of the simulation models

LOCATION / Case	Unsafe Speed Variation	Safe Speed Distributions	Yield on Circulating Roadway	Yield on Approach	Recommendation from Study Team
COLLINGWOOD TRAFFIC CIRCLE					
Case 1	X		X		
Case 2		X		X	**X**
Case 3	X			X	
Case 4	X			X	
BROOKLAWN TRAFFIC CIRCLE					
Case 1	X		X		
Case 2	X		X		
Case 3		X	X		
Case 4		X	X		
Case 5		X		X	**X**
ASBURY PARK TRAFFIC CIRCLE					
Case 1	X		X		
Case 2		X	X		
Case 3		X		X	**X**

For the Collingwood Circle three scenarios were developed. The cases included:

- "Case 1" – Existing Conditions,
- "Case 2" – Improvements suggested by NJDOT, which include realigning the Route 33/34 southbound approach and the Route 547 exit from the circle to eliminate the stop-controlled intersection on the Route 547 exit, and giving the right-of-way to circulating traffic and placing yields on the approaches,
- "Case 3" – Collection of minor improvements intended to alter speeds and headways in the traffic circle without making major geometric changes, and
- "Case 4" – Included geometric changes intended to have a larger impact on speeds.

Based on the results of each of the simulation runs, the outputs from the Case 2 simulation provided the safest output. The results of Cases 3 and 4 improved upon the existing conditions but the speed distributions through the facility were not as uniform.

For the Brooklawn traffic circle the existing conditions and four improvement scenarios were analyzed with PARAMICS. The cases included:

- "Case 1" – Existing Conditions,
- "Case 2" – Alternate 2B in the Delaware Valley Regional Planning Commission (DVRPC) *US 130 Brooklawn Circles Concept Development Report* (February 2002),
- "Case 3" – Case 2 in addition to site specific enhancements such as geometry, lighting and signage,
- "Case 4" – Alternative 2D in the DVRPC Report with the same enhancements as Case 3, and
- "Case 5" – Case 4 with yield controls on each of the approaches.

All of the simulation models produced for the Brooklawn traffic circle enhances the facility from the existing conditions. The most significant changes resulted from the enhancements located at the US 130 southbound approach as well as the geometric changes at the NJ 47 and Creek Road intersection. The study team feels that moving the yields to the approaches provides uniformity to the facility. The team also feels that, optimally, Case 5 is the most beneficial case, but Case 3 with yields on the approaches may serve as a lower cost option. The reason Case 5 is more beneficial is that the traffic patterns are changed by allowing key turning movements at the Route 130 / Old Salem Road intersection. This allows some vehicles to completely bypass the traffic circle.

For the Asbury Park traffic circle the existing conditions and two improvement scenarios were analyzed with PARAMICS. The cases include:

- "Case 1" – Existing Conditions,
- "Case 2" – Remove the inner circle and add new links on each end to create two traffic circles. This alternative also has enhancements such as geometry, lighting and signage changes, and
- "Case 3" – Case 2, plus moving all the yields to the approaches.

Presently, at the Asbury Park traffic circle the speeds within the traffic circle vary greatly. These speed variations inhibit safe operation, especially for unfamiliar users. Case 2 was modeled to enhance the traffic circle while maintaining the existing yield control structure. The speed patterns between Cases 1 and 2 are similar but with much less variability for the latter. The main enhancement in this case was the removal of the inner circle. In its place two new links were added to allow for those movements. These new links created the illusion of two separate traffic circles. Other enhancements included approach geometry changes and speed limit reductions.

The reconstruction of the inner circle as done in Cases 2 and 3 clearly has value in terms of safety. The weaving section is much greater as is the storage space behind the yield. To further enhance safety, the yields were moved to all of the approaches in Case 3. Although the PARAMICS software had trouble simulating the results by moving the yields to the approaches further investigation led the team to believe that this was beneficial in terms of safety. The team checked the delays and queue lengths against similar data for multi-lane roundabouts across the US and conclude from that comparison that the delays should be in the 10 to 25 second range per vehicle and that 95th percentile queue lengths should be between 0 and 7 vehicles except at the Route 16 approach (location c) where the existing one-lane approach should be upgraded to a two-lane approach.

Although PARAMICS had some difficulty with the modeling of the yields on the approaches, the study team found with other analysis techniques the problems would not exist. Although other options exist for this facility, Case 3 provides a lower cost option and provides uniformity within the circle.

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