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16. Abstract

This study deals with the development of a credible and valid simulation model of the Collingwood, Brooklawn, and Asbury traffic circles in New Jersey. These simulation models are used to evaluate various geometric and operational improvement alternatives. An extensive review of the available simulation packages is presented. PARAMICS microscopic simulation software was selected due to its capability of modeling and simulating complex roadway structures and driver behavior. The simulation models of these circles were developed using PARAMICS. These models were validated and calibrated using the extensive field data collected as part of this project. The specifics of the collected data, and the extraction procedure are also explained in the report. The development of the simulation models and the validation and calibration steps are presented in detail.

The study observed that the efficiency of these traffic circles is directly related to the gap acceptance/rejection of vehicles at yield-controlled or stop-controlled intersections, and the interarrival time of vehicles at the approaches. Therefore, at each selected location, gap acceptance/rejection models are developed based on the extracted data. The Application Programming Interface (API) of PARAMICS is used to incorporate site specific gap acceptance/rejection models. Also, to model realistic interarrival times at the approaches, the traffic signals at the vicinity of the circles are modeled using actual signal timing parameters.

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EXECUTIVE SUMMARY

Recently, there has been an increasing interest in improving traffic circles to address congestion and safety problems. Several states are in the process of exploring effective operational alternatives for enhancing the safety and efficiency of the traffic circles that were built in the early 20th century.

Many traffic circles were designed to handle lower traffic volumes than today's volumes. They need to be improved because they are faced with increasing congestion and safety problems. In New Jersey, 30 of the 67 traffic circles built during the 1920s were replaced by 2001. Although the replacement of these traffic circles with more efficient facilities appears to be a viable option, time and money needed for the construction of alternative designs can be prohibitive. Alternative option would be to upgrade them until they can be rebuilt.

This report focused on the analysis of the proposed operational improvements of three traffic circles in New Jersey, the Collingwood circle, the Brooklawn circle, and the Asbury circle. These circles are not roundabouts, but they are traffic circles with unusual operational and geometric designs. The priority rule that governs the roundabout traffic operations (i.e. yield at entry rule) does not always apply to these circles. The traffic flow into the circles is largely governed by the traffic signals located in the vicinity of the circles.

NJDOT has proposed operational designs that are expected to improve congestion and safety at Collingwood and Brooklawn circles. The major change is expected to be made to the Collingwood circle, where the proposed design aims to convert this traffic circle to a modern roundabout. On the other hand, the proposed design to Brooklawn circle is a medium change to the operational design of the circle. The specifics of these designs are presented in detail in this report. There are no proposed operational alternatives to the Asbury circle.

Mobility and safety are two major considerations in evaluating the efficiency of improvements to these circles.

The key findings of the simulation modeling and analysis of the circles are:

- The proposed design of the Collingwood circle does not adversely affect the congestion at the circle. Because the heavy traffic at the approaches has to yield to the circulating traffic in the proposed design, long queue times are observed in the simulation results. However, the overall efficiency of the circle is improved because the circle itself keeps operational as a result of lock-ups being removed.
- The simulation results show that the proposed design of the Brooklawn circle increases the overall network travel time, especially during the afternoon peak hours.

INTRODUCTION

Traffic circles have been used in the United States since 1905. However, their use has been limited since the 1950s, due to the realization that they worked neither efficiently nor safely [(8)]. Recently, there has been an increasing interest in improving existing traffic circles to address these efficiency and safety problems. Several states including New Jersey are in the process of exploring effective operational alternatives to enhance the safety and efficiency of traffic circles built in the early periods of the 20th century.

Many traffic circles in New Jersey, that were designed to handle lesser traffic volumes than today's volumes, fall under this category of traffic circles that need to be improved because they are faced with increasing congestion and accident problems. Although the replacement of these traffic circles appears to be a viable option, time and money needed for the construction of alternative solutions can be prohibitive. Alternative option would be to upgrade them until they can be rebuilt.

New Jersey Department of Transportation (NJDOT) has decided to seek alternative approaches to improve the Collingwood, Brooklawn, and Asbury circles in New Jersey to reduce congestion and increase safety. To assess the benefits of the operational alternative at these circles, reliable microscopic traffic simulation models of the current and proposed designs of the circles are required. The developed microscopic simulation models enable transportation analysts and planners to observe the impact of proposed modifications to the infrastructure or traffic operations in little time.

Micro simulation tools are becoming increasingly popular in traffic and transportation engineering. Many crucial planning and operational decisions, as well as the assessment of various policy alternatives are based on these simulation tools. The developers, the users, and the decision makers using the information derived from these models should be concerned with the validity of the model and its results [(11,12)]. With the increased number of off-the-shelf traffic simulation software packages, the idea of simulation and its practice has become appealing. Because of enhanced computational efficiency, the users can now develop traffic models easily, experiment with the proposed alternatives, and obtain outputs in little time. However, the use of simulation sometimes presents the potential for error. In the right hands, simulation can accomplish tremendous good when used with care [13].

BACKGROUND AND LITERATURE REVIEW

Background

William Phelps Eno first proposed the one-way rotary in 1903 for Columbus Circle in New York City. This traffic circle had a small central island, which was the distinguishing feature of traffic circles designed by Eno. In 1907, Eugene Henard proposed a gyratory traffic scheme for the Place de I'Etoile in Paris, the first gyratory in France. He felt that the size of the central island of the circle should be minimum of 8 meters. The designs of Eno and Henard greatly differed regarding the size of the central island.

The fairly low traffic volumes did not encourage the issue of the right-of-way rule in the early days, but with increase in traffic this lead to congestion at traffic circles. Wisconsin, in 1913, was the first state to adopt the yield-to-right rule, meaning entering vehicles had the right-of-way.

Increasing traffic volumes resulted in reversing the right-of-way rule at the Ellisburg traffic circle in New Jersey, and replacing the Hawthorne circle in Westchester County, New York with grade-separated interchanges. Modern roundabouts were then developed to rectify problems associated with traffic circles.

Progress in the roundabout design began in Great Britain in the 1960s. The modern roundabouts arrived in the United States in 1990 in Summerlin by Leif Ourston. The first roundabout in the United States was built in 1995—at the I-70 interchange in Vail and then the I-70 interchange in Avon, in 1998.

A modern roundabout is a form of intersection control that moderates the traffic in one direction around a circular island. Roundabouts operate with "yield at entry points" rules and give priority to vehicles within the circle. Table 1 lists some important characteristic differences between roundabouts and traffic circles.

Table 1. Distinct features of roundabouts and traffic circles [20]

	Modern Roundabout	**Traffic Circle**
Control at Entry	Yield sign for entering vehicles.	Stop, signal, or give priority to entering vehicles.
Operational Characteristics	Vehicles in the roundabout have a priority over the entering vehicle.	Allow weaving areas to resolve the conflicted movement.
Deflection	Use deflection to control low speed operation through roundabout.	Some large traffic circles provide straight path for major movement at higher speed.
Parking	No parking is allowed on the circulating roadway.	Some larger traffic circles permit parking within the circulating roadway.
Pedestrian Crossing	No pedestrian activities take place on the central island.	Some larger traffic circles provide for pedestrian crossing to, and activities on, the central island.
Turning Movement	All vehicles circulate around the central island.	At mini-traffic circles, left-turning vehicles are expected to pass to the left of the central island.
Splitter Island	Required.	Optional.

<u>Type of Roundabouts</u>

There are mainly 2 types of roundabouts:

- *Normal Roundabout*: One-way circulating roadway around a curbed central island with 13 ft or more in diameter with flared approaches to allow for multiple vehicle entry.
- *Mini Roundabout*: One-way circulating roadway around a flush or slightly raised circular island less than 13 ft in diameter without flared entries.

Why roundabouts?

Roundabouts have been shown to reduce fatal and injury accidents as mush as 76% in the USA, 75% in Australia and 86% in Great Britain [19]. The reduction in accidents is attributed to slower speeds and reduced number of conflict point. Figure 1 demonstrates the conflict points at a regular intersection and a roundabout.

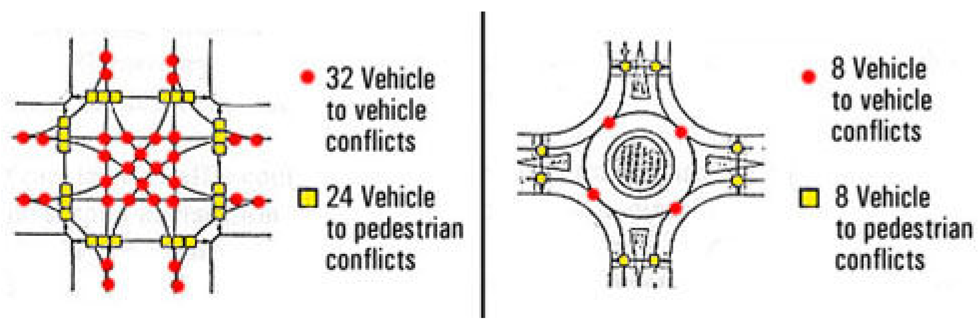

Figure 1. Conflict points of a four-way intersection and a modern roundabout [19]

The use of roundabouts decreases maintenance costs associated with traffic signals. Roundabouts handle high traffic volumes better than signalized intersections. The performance of roundabouts is usually evaluated by capacity and delay. There have been numerous literature studies that evaluated the functional performance of roundabouts. Table 2 presents details information on the advantages and the disadvantages of roundabouts.

Table 2. Advantages and disadvantages of roundabouts [20]

Category	Advantages	Disadvantages
Safety	-There is a reduced number of conflict points compared to uncontrolled intersections. -Lower operational speeds yield less severe and fewer accidents. -Slower speeds because of intersection geometry reduce accidents.	-Due to the few numbers in the US, there is likely to be an initial period where accidents are high. -Signalized intersections can preempt control for emergency vehicles.
Capacity	-Traffic yields rather than stops, often resulting in the acceptance of smaller gaps. -Roundabouts has a higher capacity/lane ratio than signalized intersections owing to the omission of lost time (red and yellow)	- Where the coordinated signal network can be used, a signalized intersection will increase the overall capacity of the network. - Signals may be preferred at intersections that periodically operate at higher than designed capacities.
Delay	-Overall delay will probably be less than that of an equivalent volume signalized intersection (this does not equate to a higher level of service). -During the off-peak period, signalized intersections with no retiming produce unnecessary delays to stopped traffic when gaps on the other flow are available.	- Drivers may not accept the geometric delays, which force them to divert their cars from straight paths. - When queuing develops, entering drivers tend to force into the circulating streams with shorter gaps. This may increase the delays on other legs and the number of accidents.
Cost	-In general, less right-of-way is required. -Maintenance costs of signalized intersections include electricity, maintenance of loops, signal heads, controller and timing plans (roundabout maintenance includes only landscape maintenance, illumination, and occasional sign replacement). - Accident costs are low due to the low number of accidents and severity.	-Construction costs may be higher. -In some locations, roundabouts may require more illumination with increasing costs.

(Table 2 Continued)

Pedestrians and Bicyclists	-A splitter island provides a refuge for pedestrians that will increase safety. -At low speed and low traffic volume, roundabouts improve safety for bicyclists.	-A splitter island may cause difficulty to people using wheelchairs. -Tight dimensions of roundabouts create an uncomfortable feeling to bicyclists. - Longer paths increase travel distances for both pedestrians and bicyclists. - Roundabouts may increase delay for pedestrians seeking acceptable gaps to cross.

The use of roundabouts may not always result in reduced delays or accidents. In certain situations a roundabout may not be effective. For example, a roundabout may cause longer delays at traffic intersections where traffic flows at different directions are unbalanced, where a major road intersects a minor road. Factors such as insufficient space for satisfactory geometric design or oversize vehicles, unfavorable topography or high costs may at times lead to consideration for not constructing a roundabout at that particular intersection. Roundabouts may prove to be ineffective at an isolated intersection in a network of consecutive traffic signals or where there is frequent pedestrian activity.

Many traffic circles need to be analyzed for various operational improvements to increase their efficiency. With the implementation of various improvement measures, these traffic circles can be converted to roundabouts. The operational improvements that can be considered in general for traffic movement specific to traffic circles are listed below.

Operational Improvements Specific to Traffic Circles

- Yield-at-entry rule to prevent high-volume roundabouts from locking up.
- Adequate vehicular deflection at all entry points.
- Smaller diameters to eliminate weaving and instead make the driver concentrate on gap acceptance only.

- Widening the road slightly at entry points to provide for large increases in capacity.
- Eliminate traffic signal equipment.
- Use raised central island to mark transition from one class of road to another.
- Eliminate left turn movements.
- Miscellaneous improvements—such as greater entry deflection, yield signs, “YIELD AHEAD” signs, yield lines, and “YIELD” legends.
- If there are traffic signals at the approach to traffic circles, they should be synchronized to relieve weaving within the circle.

Literature Review

There are numerous literature studies about the design, safety, and efficiency of roundabouts. Much of this previous work focused on the determination of the capacity of roundabouts. The most common conclusion is that the capacity of roundabouts mainly depends on its geometric features. For example, Polus and Shumeli [(21)] define the capacity of a roundabout for each entry, and not for the entire roundabout. It is usually considered that the entry capacity depends entirely on the geometric characteristics of the roundabout. The study indicates an exponential decrease in entry capacity with the increase in circulating flow (See Table 3 and Table 4). Similarly, Al-Masaeid and Faddah [(23)] developed an empirical model for estimating roundabout entry capacity for the conditions in Jordan and defined an exponential relationship between entry capacity and circulating traffic flow. Their analyses indicate that the circulating traffic flow, widths of entry and circulating roadway, central island diameter, and distance between an entry and a near-side exit all have a significant influence on entry capacity.

Roundabouts in many countries are studied and modeled as “T-intersections”. Brilon and Stuwe [(26)] specified the traffic circle capacity in terms of number of lanes within the circle and in the entry. They consider the roundabout as a series of T-shaped entries into a one-way circular road. Brilon and Stuwe [26] also discussed the traffic safety at roundabouts. They listed the principles for a safe traffic circle design as follows:

- Clarity and visibility of traffic situation.
- Comprehensibility of traffic operations.
- Possibility for the largest vehicles (such as trucks or articulated buses) being permitted.

In Australia, Troutbeck [25] used gap-acceptance approach for estimating the capacity of traffic circles. This approach as a function of traffic circle geometry has improved the ability to account for differences resulting from the geometric design, but ignores the influence of heavy vehicles. To consider the effect of heavy vehicles, the gap acceptance parameters were modified. The capacity of a traffic circle was evaluated as a series of T-intersections. The circulating traffic is the traffic flow past the entering vehicles that opposes their entry. The entry lane flows are the other traffic inputs. In this study, two types of delays were considered:

- Queuing delay, which is a function of gap-acceptance parameters and flows on circulating and entry lanes.
- Geometric delay, which depends on the proportion of drivers stopped and the distance traveled around the traffic circle at the slower negotiation speed (See Table 3 and Table 4).

Several other studies have been performed on design related issues of old traffic circles and modern roundabouts. Bared et al. [22] discussed the practical issues related to design, operation, and traffic regulations at roundabouts. They also looked at justification, safety and accident prediction, capacity, delays, location, design considerations, bicycle considerations, and pedestrian considerations.

Table 3. The entry capacity equations considered in various studies

Literature	Equations	Variable Definitions
Polus and Shmueli (1997)	$V_e = Ae^{-(BV_c)}$	V_e: entry capacity A: entry capacity for a very low circulating flow B: the curvature of the model
Al-Masaeid and Faddah (1997)	$q_e = e^{8.68-6.74q_c/10,000}$	q_e: entry capacity (pcu/hr) e: base of natural logarithm q_c: circulating traffic flow (pcu/hr)
Troutbeck (1993)	$C = \dfrac{\alpha q_c e^{-\lambda(t_a-\tau)}}{1-e^{-\lambda t_f}}$	C: absorption capacity of an entry lane (veh/sec) α: proportion of free vehicles in circulating streams q_c: flow of vehicles in circulating streams (veh/sec) or $Q_c/3600$ t_a: critical acceptance gap t_f: follow on time τ: minimum headway in circulating streams, and these are related by $\lambda = \alpha q_c/(1-\tau q_c)$
Brilon and Stuwe (1993)	$q_{e,\max} = A.e^{-B/10,000.q_c}$	$q_{e,\max}$: maximum possible traffic volume of the entry in pcu/hr. q_c: traffic volume in the traffic circle at the entry in pcu/hr. A and B are constants.

Table 4. Summary of capacity models used in different countries

Paper	Equations	Variable Definitions
Bared, Prosser and Tan Esse (1997): Capacity model from Great Britain	$C = k(F - f_c Q_c)$ $k: 1 - 0.00347(\phi - 30) - 0.978[(l/r) - 0.05]$ $F:\ 303x_2$ $f_c:\ 0.21t_p(1 + 0.2x_2)$ $t_p:\ 1 + 0.5/(1 + M)$ $M: \exp[(D - 60)/10]$ $x_2:\ v + (e - v)/(1 + 2S)$ $S:\ 1.6(e - v)/l'$	C: approach entry flow capacity in pcu/hr Q_c: circulating entry flow (pcu/hr) D: inscribed diameter (m) r: entry radius (m) l': flare length (m) e: entry width (m) v: approach width (m) ϕ:entry angle(degree)
Bared, Prosser and Tan Esse (1997): Capacity model from France	$C = (1{,}330 - 0.7QG)[1 + 0.1(le - 3.5)]$ Q_x': $Q_x(15 - ls)/15$ (if ls >15 m Q_x' =0) QG: $(Q_c + 2/3Q_x')[1 - 0.085(lc - 8)]$	C: approach entry flow capacity in pcu/hr ls: separator island width (m) measured at the markings le: entry width (m) between line markings or edge of gutters lc: width of circulatory roadway between line markings or edge of gutters (m) Q_c: circulating flow at the entry (pcu/hr) Q_x: exiting flow (pcu/hr)
Bared, Prosser and Tan Esse (1997): Capacity model from Germany	$C = A - BQ_c$	C: approach entry flow capacity in pcu/hr Q_c: circulating flow at entry (pcu/hr) A and B depend on the number of lanes on the facility

Mandavilli [27] discussed the increasing positive response to roundabouts and their benefits. He concluded that the increased safety levels at roundabouts were due to fewer conflict points, reduced speed, clear right of way to pedestrian, etc. The increasing use of roundabouts led to increased safety, lower cost, reduced consumption and vehicular emissions and reduced noise. He considered various measures of effectiveness for the analyses of a roundabout, such as average queue length, degree of saturation, average intersection delay, maximum approach delay, proportion of vehicles stopped, and maximum proportion of vehicles stopped.

The acceptance and the increasing use of roundabouts in the United States are also discussed in the *Synthesis of Highway Practice 264: Modern Roundabout Practice in the United States* [(39)]. This study distinguishes the modern roundabouts from traffic circles based on the design principles. The old operational design of traffic circles gave priority to entering traffic and was designed to minimize the weaving movement. The circles became large in size, with long distances between consecutive entrances and exits and with relatively high speeds. In contrast, the modern roundabouts are designed for lower speeds and their dimensions are determined by the number of highways connected, the capacity of the roundabout, and the turning radii of larger vehicles. This report delineates the main reasons for building roundabouts which are greater safety considerations, shorter delays, lower costs, and aesthetic and urban design advantages. It shows that roundabouts can bring a sense of place to an intersection and improve the visual quality for drivers as well as for the non-driving public. The most appropriate applications for roundabouts are considered to be at locations where space for queue storage is insufficient. Interchanges and intersections near tunnels and bridges are also best suited for roundabouts.

Review of Traffic Simulation Packages

In recent years computer simulation has become one of the most widely used and powerful tools for studying the current network characteristics and predicting the likely effects of the desired system under various traffic demand and network conditions. Computer simulation is proving to be a very helpful analysis and design tool for testing the proposed system components before implementation.

With the continuous introduction of advanced computer technology solutions, traffic simulation has developed from a research tool used by a limited group of experts to a widely used technology in the research, planning, demonstration, and development of traffic systems. Today, many commercially available traffic software packages can simulate network-wide traffic flows under short and long-term variations in travel demand, under various random events such as road closures, incidents, and route diversions, and can also collect detailed results on vehicle delays, link travel times, stop times.

Most of the traffic simulation software packages are either based on microscopic or macroscopic traffic flow models, which use either a stochastic or deterministic approach to generate simulated vehicles. With the increasing number of roundabouts, many simulation softwares designed specifically for roundabout design and analysis have been developed.

In addition to the general-purpose traffic simulation packages commercially available in the market, software packages designed for the analysis and design of roundabouts only are briefly discussed in this section.

Table 5. Software packages for traffic simulation

Common Software Packages		Software Packages for Roundabouts
PARAMICS	AIMSUN2	ARCADY
VISSIM	NEMIS	RODEL
CORSIM	TRANSIMS	SIDRA
INTEGRATION	TRANSYT	HCS 2000
SIMTRAFFIC	WATSIM	KREISEL
SATURN	HUTSIM	GIRABASE
DRACULA	CARSIM	SIGROUND
GETRAM	MITSIM	SIMRO

General Purpose Traffic Simulation Software Packages

In this section, the available commercial software packages are discussed.

PARAMICS- PARAllel MICroscopic Simulation

PARAMICS is an advanced suite of software tools for microscopic traffic simulation developed by Quadstone Limited. It is used to model the movement and behavior of individual vehicles on urban and highway road networks. It allows users to customize many features of the underlying simulation model through Application Programming Interfaces (API).

Accurate geometry of the network and smooth coding of links in PARAMICS are important for simulation results because the driver's behavior relies on characteristics of drivers and vehicles, the interactions between vehicles, and network geometry. PARAMICS has the ability to obtain detailed state variable information on each vehicle on time scales with better than second-by-second accuracy. The basic input data for the simulation are a road network and time dependent traffic demand (origin destination (OD) demand matrix). PARAMICS determines the shortest path for each vehicle and reconsiders this path at each intersection. The actual traffic situation, knowledge of local routes and the presence of route advice (VMSs or onboard route navigation systems) all influence the final route.

PARAMICS is controlled via a graphical user interface (GUI), which visualizes the network and simulated traffic in two or three dimensions. The results of the simulation are presented in a lively and comprehensible way for customers and other interested people. A significant disadvantage of the PARAMICS model is the use and reliance on OD matrices to derive traffic volumes.

VISSIM- VISual SIMulation

VISSIM was developed at the University of Karlsruhe, Germany, with commercial distribution beginning in 1993 by PTV Transworld AG. It is a microscopic, time-step, and behavior-based simulation software developed to analyze the full range of functionally classified roadways and public transportation operations.

It includes modules ranging from demand forecasting to detailed intersection control analysis and simulation. VISSIM can analyze traffic and transit operations under a variety of policy constraints, making it a useful evaluation tool. It features quality animation capabilities.

VISSIM uses the Wiedemann car following model, which represents the psychological processes of the driver to obtain a desired following distance and relative speed to the lead vehicle. Dynamic ramp metering and signal control can be evaluated, and external interface through API is possible. The model features an intuitive, easy-to-learn GUI, with all geometry and traffic control features available for editing via a simple graphical menu. It also has a dynamic assignment routine, which can be used to determine the user-equilibrium (UE) driver route choice based on observed travel times through the network, such as routine congestion, bridge closure, and delay at signalized intersections.

VISSIM should be considered for urban environments that contain transit or pedestrians (or both). It has detailed representation of passenger boarding and alighting at bus stops, and available algorithms to emulate the Transit Signal Priority (TSP) operation in the leading traffic signal controllers.

It consists of an integrated set of simulation models that represents the traffic environment. Its component models are:

- NETSIM, a microscopic stochastic simulation model of urban traffic.
- FRESIM, a microscopic stochastic simulation model of freeway traffic.
- NETFLO, a macroscopic simulation of urban traffic.
- FREFLO, a macroscopic simulation of freeway traffic.

The naming system for these models is based on a combination of prefixes and suffixes.

- NET- surface street network.
- FRE- freeway network.
- SIM- microscopic simulation.
- FLO- macroscopic simulation.

The combination of NETSIM and FRESIM is named CORSIM, for corridor microscopic simulation.

The combination of NETFLO and FREFLO is named CORFLO, for corridor macroscopic simulation.

CORSIM- CORridor SIMulation

CORSIM is a combination of two microscopic models, NETSIM and FRESIM.

Within the earlier integrated traffic simulation system (TRAF), the freeway/urban street system, simulated with the combination of NETSIM and FRESIM, were composite rather than integrated networks. A Windows version of TSIS (Traffic Software Integrated System) was developed to provide an integrated and user-friendly environment.

CORSIM simulates traffic and traffic control systems using commonly accepted vehicle and driver behavior models. It is a comprehensive microscopic traffic simulation, applicable to surface, streets, freeways, and integrated networks with a complete selection of control devices (i.e., stop/yield sign, traffic signals, and ramp metering).

CORSIM offers specific advantages in its ability to:

- To model complicated geometry conditions.
- To simulate different traffic conditions.
- To simulate different traffic control management and operation.
- To account for the interactions between different components of networks.
- To interface with external control logic and programs.
- To model time varying traffic and control conditions.

INTEGRATION

INTEGRATION is a simulation model developed primarily for research use that has recently been distributed on a commercial basis. Integration does not have an API or access to vehicle state variables on a time step-by-time step basis. Integration appears to be weaker at explicit simulation of detailed vehicle-to-vehicle interactions than other simulation models, given that it originated from a hybrid "mesoscopic" macro/micro modeling base. Integration does not appear to explicitly model movements in the intersection box. Integration has been modified to predict crash rate statistics using previously developed nonlinear regression models (based on link mean speed).

INTEGRATION can simulate U-turns, but it also is least able to model complex signal operations. On the other hand, it models only the aggregate speed-volume interactions of traffic and not the details of a vehicles' lane-changing and car-following behavior; thus, it is commonly classified as a mesoscopic integrated simulation model. Integration is a routing-oriented model for mixed networks; vehicles' trip origins, destinations, and departure times are specified externally to the model.

SIMTRAFFIC- TRAFFIC SIMulation

Developed by Trafficware, SIMTRAFFIC is an easy-to-use traffic simulation tool that is designed for use by field traffic engineers primarily as an adjunct to the SYNCHRO signal-timing optimization software. It has a link-node structure; and offers a simple and quick data entry GUI. A significant disadvantage of SIMTRAFFIC is the lack of API functions and supporting detailed output of vehicle-state variable information and automated statistical analysis capabilities of other codes. On the other hand, SIMTRAFFIC has the most resolute state variable standard update intervals of all models surveyed (0.1 s) and claims many improvements on the CORSIM models for representing real-world traffic conditions, although the validity of those improvements has not been determined.

SIMTRAFFIC is used to create input files for CORSIM. It can be used for traffic signal optimization studies, traffic impact studies, and corridor studies. It does not have transit capabilities and is not a multi modal tool, but can be used only for pedestrians. The output cannot be visualized in 3-dimensional format.

SATURN- Simulation and Assignment of Traffic to Urban Road Networks

SATURN is a flexible network analysis program suite developed at the Institute for Transport Studies, University of Leeds and distributed by WS Atkins of Epsom since 1981.

Its approach combines traffic simulation and assignment model for the analysis of road-investment schemes ranging from traffic management schemes over relatively localized networks through to major infrastructure improvements. It performs as a:

- Traffic assignment model
- Simulation model of individual junctions
- Network editor, database and analysis system
- Matrix manipulation package for the production of matrices
- Trip matrix demand model covering the basic elements of trip distribution, modal split etc.

SATURN possesses powerful graphical display capabilities for network, junction and matrix-based data. The other options available allows for on-screen cordoning, select link reassignments, GIS-style background displays, animated queues, data editing and tree building.

Its matrix manipulation program offers a full range of interactive matrix operations as required by standard transport planning applications, e.g. matrix building, editing, factoring, furnessing, transposing etc. It also provides easy transfer between SATURN and other transport and spreadsheet packages.

DRACULA- Dynamic Route Assignment Combining User Learning and microsimulation

DRACULA is a dynamic network microsimulation model developed at University of Leeds since 1993. It offers a new approach to modeling road traffic networks, in which the emphasis is on the "micro-simulation" of individual trip makers' choices and individual vehicles' movements.

It represents directly driver choices as they evolve from day to day combined with a detailed within-day traffic simulation model of the space-time trajectories of individual vehicles according to car-following, lane-changing rules and intersection regulations. It therefore provides strong interaction between demand and supply.
The current release version is named DRACULA-MARS (Microscopic Analysis of Road Systems)

GETRAM-Generic Environment for TRaffic Analysis and Modeling

GETRAM is a simulation environment comprising a traffic network graphical editor (TEDI), a microscopic traffic simulator (AIMSUN2), a network database, a module for storing results, and an API to aid interfacing to assignment models and other simulation models.

AIMSUN2- Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks

AIMSUN2 is a software tool, which is able to reproduce the real traffic conditions of any traffic network on a computer. It is mainly used for testing new traffic control systems and management policies or for the evaluation of the different options for implementing a new infrastructure before building it. The behavior of every single vehicle in the network is continuously modeled throughout the simulation period, using several driver behavior models (car following, lane changing, and gap acceptance).

The main features of this simulation model are:

- It can deal with different traffic networks and can model different types of traffic controls.
- Two different types of simulation are involved: The first is based on input traffic flows and turning proportions, where vehicles are distributed stochastically around the network, and the second is based on OD matrices and route selection

models, where vehicles are assigned to specific routes from the start of their journey to their destination.

- It provides a picture of the network and an animated representation of the vehicles in it. Through the interface, the user may access any information in the model and define traffic incidents before or during the simulation run.
- Environmental measurements, such as fuel consumption and pollution emissions, are also provided.
- A standard interface to external adaptive traffic control systems, such as SCOOT or C-Regular, is available.

NEMIS

NEMIS is a scientific software package, used principally for research and development work and for the technical assessment of traffic control strategies. It was designed as a specific solution to the problem of on-street testing. It is capable of modeling urban networks and vehicle behavior in considerable detail and is well structured to meet a variety of application needs. Its usefulness has been demonstrated for the following tasks:

- Analyzing of the effects of regulation and network modification on traffic mobility.
- Evaluating different traffic light control strategies.
- Testing traffic assignment techniques.
- Simulating and evaluating route guidance strategies and variable message systems.
- Evaluating the effects of improved public transport facilities on inner city traffic flow.
- Testing the effectiveness of parking management systems.
- Examining strategies aimed at reducing fuel consumption/exhaust emission.

TRANSIMS- TRansportation Analysis and SIMulation System

TRANSIMS is an integrated system of travel forecasting models designed to give transportation planners accurate, and complete information on traffic impacts, congestion, and pollution. It was developed to meet the Clean Air Act, the Intermodal

Surface Transportation Efficiency Act, Transportation Equity Act for the 21st Century, and other regulations. It consists of coordinated models and databases that create a virtual metropolitan region that fully represent the region's transportation infrastructure, its inhabitants, and their activities. It then simulates the movement of individuals across the transportation network on a second-by-second basis, mimicking the traveling and driving behavior of real people in the region.

TRANSIMS starts with data about people's activities and the trips they take to carry out those activities, and then builds a model of household and activity demand. The model forecasts how changes in transportation policy or infrastructure might affect those activities and trips. It tries to capture every important interaction among travel subsystems, such as an individual's activity plans and congestion on the transportation system. TRANSIMS tracks individual travelers and therefore can evaluate transportation alternatives and reliability to determine who might benefit and who might be adversely affected by transportation changes.

TRANSYT

TRANSYT is a complete traffic signal timing optimization software package for traffic networks, arterial streets, or single intersections having complex or simple conditions. Its strength lies in its ability to simulate traffic conditions in a level of detail beyond other optimization programs.

TRANSYT is also one of the most comprehensive signal timing tools available. It has broader capabilities compared with other signal timing programs, including:

- Detailed simulation of existing conditions.
- Optimization of cycle length, phasing sequence, splits and offsets.
- Detailed analysis of traffic-actuated control.
- Optimization based on a wide variety of objective functions.
- Hill-climb and genetic algorithm optimization.
- Explicit simulation of platoon dispersion, queue spillback and spillover.
- Multi-cycle and multi-period simulation.

- Full flexibility in modeling unusual lane configurations and timing plans.
- Full flexibility in modeling English and metric units, right-hand and left-hand driving.

TRANSYT has evolved into a benchmark within the transportation profession. It has facilitated greater understanding of signal timing optimization, while continuing to improve traffic operations as a result of its designs being widely implemented in the field.

WATSIM- Wide Area Traffic SIMulation

WATSIM is an enhancement of the NETSIM model by one of the original developers of NETSIM. As such, WATSIM inherits many of the limitations of the CORSIM model, including fixed 1-second time steps. WATSIM has many additional advantages over CORSIM, including light-rail modeling. WATSIM lacks many of the features of general-distribution tools for supporting this type of surrogate safety research, such as configurable output files, post-processing tools, and APIs.

CARSIM- CAR-following SIMulation [31]

CARSIM simulates not only normal traffic flow but also stop-and-go conditions on freeways. CARSIM includes the following features:

- Marginally safe spacing is provided for all vehicles.
- Start-up delays of vehicles are taken into account.
- Reaction times of drivers are randomly generated.
- Shorter reaction times are assigned at higher densities.
- Dual behavior of traffic in congested and non-congested conditions is considered in developing the car-following logic of this model.

The validation of CARSIM has been performed at microscopic and macroscopic levels.

MITSIM- MIcroscopic Traffic SIMulator

The traffic and network elements are represented in detail to capture the sensitivity of traffic flows to the control and routing strategies. The main elements of MITSIM are:

- *Network Components:* The road network along with the traffic controls and surveillance devices are represented at the microscopic level. The road network consists of nodes, links, segments (links are divided into segments with uniform geometric characteristics), and lanes.
- *Travel Demand and Route Choice:* The traffic simulator accepts as input time-dependent origin to destination trip tables. These OD tables either represent expected conditions or are defined as part of a scenario under evaluation. A probabilistic route choice model is used to capture drivers' route choice decisions.
- *Driving Behavior:* OD flows are translated into individual vehicles wishing to enter the network at a specific time. Behavior parameters (such as desired speed, aggressiveness, etc.) and vehicle characteristics are assigned to each vehicle/driver combination. MITSIM moves vehicles according to car-following and lane-changing models. The car-following model captures the response of a driver to conditions ahead as a function of relative speed, headway and other traffic measures. The lane-changing model distinguishes between mandatory and discretionary lane changes. Merging, drivers' responses to traffic signals, speed limits, incidents, and tollbooths are also captured. Rigorous econometric methods have been developed for the calibration of the various parameters and driving behavior models.

Simulation Software Packages Specific to Roundabout Modeling

One important question in the roundabout design is its traffic capacity. With the widespread adoption of roundabouts and the sharp reduction of the high potential of speed angle crashes, roundabout designs generally result in fewer serious injuries, crashes, and fatalities. Many software packages have been developed exclusively for the design and analysis of roundabouts. A brief description of these software packages is presented below.

ARCADY- Assessment of Roundabout CApacity and DelaY

ARCADY was developed by Transportation Research Laboratory (TRL), United Kingdom, and its distributor is Systematica North America. It's based on UK empirical equations. It addresses all roundabout configurations and also includes a crash prediction model. It is restricted to 50% confidence limits and requires detailed knowledge of geometry. Calibration of this software to US capacity is unknown at this time.

Data were collected at extensive field studies and from experiments involving drivers at temporary roundabouts. Empirical relationships were developed from the data and incorporated into ARCADY. This model reflects British driving behavior and British roundabout designs.

RODEL- ROundabout DELay

RODEL was developed by Barry Crown, United Kingdom, and its distributor is Rodel Software Ltd., United Kingdom. It's based on UK empirical equations. It can be used for all configurations including multiple roundabout interactions. The approach in it includes design mode (performance targets specified) and evaluation mode (geometric parameters specified). It allows user specified confidence limits and uses spreadsheet style format. It also includes a crash prediction model and assists user in developing an appropriate roundabout for the traffic conditions. However, it requires a detailed knowledge of the roundabout geometry, and its calibration to US capacity is unknown at this time.

SIDRA- Signalized and unsignalized Intersection Design and Research Aid

SIDRA was developed by Akcelik and Associates Pty Ltd., Australia, and its distributor is McTrans Center (University of Florida). It is based on the Australian method with analytical extensions. It finds application in all configurations and other control types. It can evaluate two-way stop control (TWSC), all-way stop control (AWSC) junctions, and traffic signals. It also provides US, Highway Capacity Manual (HCM) 97, and German procedures. It uses lane-by-lane modeling for all types of interactions.

SIDRA is based on gap acceptance processes. It uses field data for gap acceptance parameters to calibrate the model. There has been limited field evaluation of the results; however, experience has shown that results fit Australian and US single-lane roundabout conditions satisfactorily. An important attribute is that the user can alter parameters to easily reflect local driving conditions.

HCS 2000 – Highway Capacity Software 2000

HCS2000 is the most commonly used software by the highway authorities. It is an analytical model based on the HCM 2000 as well as signalized TWSC and AWSC procedures. It is used for analyzing single-lane roundabouts with a limited range of volumes. But it does not estimate delay and queuing. Its application is limited to capacity estimation based on entering and circulating volume. The optional gap acceptance parameter values provide both a liberal and conservative estimate of capacity.

GIRABASE ("GIRABSE: Calculation of Roundabout Capacity")

GIRABASE was developed by Bernard Guichet, France, and its distributor is CERTU, France. The software is basically designed in French, but it has an English language adaptation. It uses French empirical equations. It estimates capacity delay and queuing based on regression and is sensitive to geometric parameters. It also recommends design modifications. It currently has limited use in the United States.

GIRABASE enables the verification of:

- The existence and cause of possible malfunctions.
- The efficiency of envisaged solutions.
- The capacity of a roundabout to receive additional traffic.

GIRABASE processes grade-separated roundabouts, semi-traversable roundabouts and mini-roundabouts. However, GIRABASE cannot be applied to "priority to the right" roundabouts or to those controlled by traffic lights. The GIRABASE program calculates, for all the arms of the roundabout, the following values:

- The reserve capacity in percentage.
- The reserve capacity in pcu/h.
- The average waiting time in seconds.
- The total waiting time in hours.
- The average queue length in number of vehicles.
- The maximum queue length in number of vehicles.

SigRound- Signal controlled Roundabout

SigRound is developed by Paul Moore of JCT Consultancy. It is designed to deal with the common problems associated with the analysis and design of signal roundabouts. It focuses on lane flow continuity, lane discipline, and traffic signal control. The current analysis methods include manual calculations; a standalone junction analysis software, LINSIG; use of TRANSYT; and microsimulation.

SigRound helps with the design of traffic signal roundabouts by allowing the user to graphically design the lane structure, traffic flow assignments and signal coordination. This software is still not on the market.

SIMRO- SImulation Model of Roundabout Operations

SIMRO was developed to evaluate different designs of roundabouts operating under the offside priority rule. The key areas of the model are: vehicle kinematics, vehicle generation, free-flow acceleration and deceleration, car-following behavior, gap-acceptance behavior and lane changing at flares. The validation studies have shown that SIMRO provides a good representation of real-world conditions.

The selection of a software package to analyze existing traffic conditions at a traffic circle, as well as the impact of proposed operational scenarios resulted from the literature review and the meetings with the NJDOT staff. The major considerations were as follows:

- A state-of-the-art GUI that allows the research team to visually observe the output of the traffic simulation model is required. This GUI is deemed to be the most important validation and analysis tool for the NJDOT.
- A microscopic model of the traffic flow is needed to understand the interaction among individual vehicles such as merging, weaving, lane change etc.
- The selected software package should be sophisticated enough to model various traffic control strategies ranging from stop signs to traffic responsive metering.
- The selected software package should be commercially available and supported by a team of software developers that can quickly respond to questions regarding advanced use of the package.

Selection of PARAMICS Simulation Software

The PARAMICS simulation tool appears to satisfy all the modeling and simulation requirements of the traffic circles because of the following advantages over other existing traffic simulation tools:

- Unmatched graphical representation of the simulated traffic conditions.
- Excellence in modeling highly congested networks and ITS infrastructures.
- Capability of modeling individual vehicles in fine detail for the duration of their entire trip, providing accurate traffic flow and congestion information, as well as enabling the modeling of the interface between drivers and ITS (Abdulhai et al, 1999).
- Capability of microscopically modeling the vehicle-following and lane-changing behavior of individual vehicles.
- Capability of incorporating driver and vehicle performance measures.
- Capability of modeling ITS strategies such as traffic responsive merge control, traffic responsive signals, variable speed limits, various traffic detection strategies without major modifications to the original simulation package.
- Batch mode operations for detailed statistical studies that require large number of simulation runs to ensure the reliability of the results obtained.

- API option, which enables users to modify the simulation logic and models that are part of the original PARAMIC package. API provides the modelers with the flexibility of testing their own models developed as a result of specific project needs.

Based on the detailed assessment presented in this section, it is clear that PARAMICS satisfies all the major requirements of the parties involved in this project.

MICROSCOPIC SIMULATION APPROACH

Simulation modeling and analysis include (1) model verification, (2) model validation and calibration, and (3) output analysis. A thorough process of development of a valid simulation model is crucial for ensuring reliable information gathered from these simulation models.

Model Verification

Model verification entails building the model correctly. This stage deals with accurately transforming the model concept from a simulation flowchart into a model specification using a computer program [(1)]. The accuracy of this stage depends on the reliability of the software used.

Model Validation and Calibration

Model validation and calibration is the process of obtaining a desired confidence level of the model and its results. The questions of concern are the following: (1) Are the assumptions underlying the model correct?; (2) Are the parameters of the input statistical distributions correct?; and, (3) Are the model's input-output transformations correct? [(11)].

Real world data are necessary to answer the preceding questions. Input data include geometrical and operational properties of the network such as curvature, number of lanes, signposting, traffic signals, and traffic characteristics, such as OD demand matrices, inter-arrival times of vehicles, gap acceptance/rejection, and so forth. Output data include traffic volumes, average vehicle travel and wait times, and queue lengths, queue times.

The validation process ascertains that the output data obtained from the simulation model driven by the input data are close to the real-world system output data. Each output variable is assumed to belong to a statistical distribution. The mean of the population of this variable, μ_1 and the mean of the simulated output variable, μ_2 should be theoretically the same for the analyst to assert that the simulation model is statistically valid. However, in most cases, the analyst does not have prior knowledge of the probability distribution of the output variables. Thus, to test the significance of the null hypothesis $\mu_1 - \mu_2 = 0$, central limit theorem is utilized, where large samples of the variable are collected, and the sampling distribution of μ_1 and μ_2 are assumed approximately normally distributed. Because the variance of output variables is not available, Student *t*-distribution is used to construct a confidence interval for the population mean (Refer to Law and Kelton (7) for more explanation).

When comparing the system and model output data, if there are substantial differences, some correction factors are added to the input data. Then the model and system output data are compared again. This procedure of input modification to meet the target output measures is called calibration**.** Calibration is needed when there are insufficient data to represent the real world system. For example, driver characteristics such as patience, awareness and reaction time data greatly affect network performance and are very difficult to collect. Calibration is used when there is a lack of such data.

Output Analysis

"In many simulation studies, a great deal of time and money is spent on model development and programming, but little effort is made to analyze the simulation output data appropriately" (6). This is, without a doubt, a familiar case in traffic simulation studies. Stochastic processes are random events; their outcomes are also random. If the model is validated correctly, the output (or response) of the system obtained from a single simulation run is just a glimpse of what it actually is. Thus a thorough statistical analysis is required to determine the output measures within an acceptable degree of confidence.

Simulation of systems is a meticulous procedure that requires time, effort and money. Traffic micro-simulation modeling is, in particular, more complicated due to the following reasons:

- The performance of the network is highly affected by driver's decision and characteristics. However, these cannot be simulated perfectly (i.e., lane changing, route choice, reaction/perception times).
- The study network often includes several highways, intersections and interchanges. Even in a small model there are numerous input and output parameters.
- The data required for modeling the input distributions and the output data required for validating the model cannot be easily obtained.
- As the size of the network increases, the effort to validate the model and analyze the output increases because of high computational costs. (Refer to [6] for more detailed discussion).

SIMULATION MODEL DEVELOPMENT IN PARAMICS

This section presents the simulation model development and analysis of the Collingwood, Brooklawn and Asbury traffic circles in New Jersey using PARAMICS. The steps of building a valid and reliable simulation model (explained above) are applied for the modeling of these traffic circles. Each section presents a description of the proposed alternatives. Verification, validation, and calibration efforts for each model are explained in detail.

Collingwood Circle

The current and proposed designs of Collingwood Circle are modeled using PARAMICS simulation software. PARAMICS is used to model the movement and behavior of individual vehicles on urban and highway road networks. Figure 2 and Figure 3 show the simulation models of the current and proposed designs of the circle developed in PARAMICS. These networks consist of 120 nodes and 266 links in average, as well as 21 demand zones.

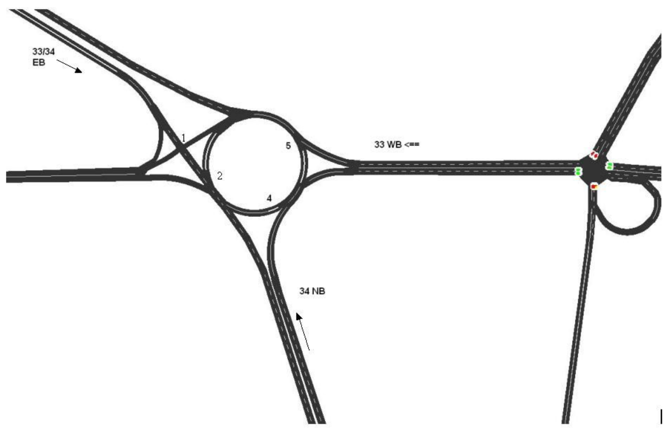

Figure 2. Simulation model of current design

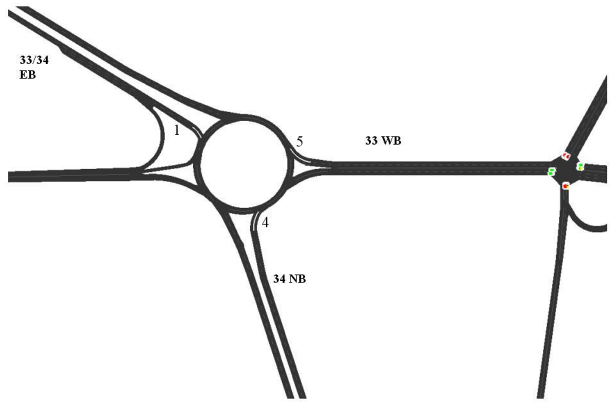

Figure 3. Simulation model of proposed design

Model Verification

Model inputs related to infrastructure such as number of lanes, speed limits, signposting distances, barred turns, and jug handles were collected during the site visits. The models were then simulated at varying levels of traffic volume and using different random number streams to observe whether vehicles actually behave reasonably (i.e., correct turns, accepting priority movements at junctions, proper lane changing, using correct lanes while exiting the roadway, etc). This step is crucial in detecting any obvious errors in the model.

Description of Data

Traffic data were collected at the circle on October 24, 2003 from 7 a.m. to 5 p.m. using a portable tower video surveillance system (POGO) with two dome cameras and two infrared cameras (Figure 4); a portable mast with a Sony camcorder and an omni-directional camera; and, two camcorders at the circle approaches. The recorded traffic data were then extracted in Rutgers Intelligent Transportation Systems Laboratory. The extracted data include (1) vehicle counts at 11 locations a ever hour with the percentage of trucks and passenger cars, (2) vehicle inter-arrival times at three major priority approaches, (3) vehicle wait time before yield signs at five locations, and (4) gap acceptance/rejection times at four yield signs.

It should be mentioned that traffic data collection and extraction is a very expensive and time-consuming task. Extracting one day of traffic data took approximately two weeks with two students.

Figure 4. Portable tower video surveillance system (POGO)

Model Validation and Calibration Efforts

The simulation model is compared with the real world circle via utilizing various tests: subjective tests and objective tests.

Subjective tests involve experts of the system who can make judgments about the model and its outputs. Therefore, the developed model was loaded on a computer at the NJDOT headquarters, where the experts could run the simulation and comment on the shortcomings of the model. Also the simulation models were shown to NJDOT staff at several meetings, and their feedback was incorporated in the subsequent steps of the model development. This interactive validation (i.e. face validation) is extremely important in model development because it allows the modeler to incorporate expert judgment, which is not easily attainable.

Objective tests require ground truth data to be used in statistical tests to compare various aspects of the system data with the same aspects of the model data set. However, because only one set of traffic data is available, it can only be used for a first stage validation process [(3)]. It is assumed that the average of the ground truth data for each output variable is the mean of its population. As more system behavior data are gathered, the validity of the model can be further improved. A complete statistical analysis can be performed as explained in the **Model Validation and Calibration** section. Input-output transformations of the model can be observed and compared with the system input-output transformations that are determined by the independent sets of system data.

Modeling of Origin – Destination Matrices

OD demand matrices are extracted for each hour by using the observed traffic volumes at eleven locations at the circle using a trial and error process. It is obvious that the hourly traffic volume at each location is different every day and is assumed to be normally distributed. The simulation model is run with different random number seeds. At each location the traffic count for every replication is independent and identically distributed, thus the sample mean is an unbiased estimate of the true mean. Since the variance of the traffic volume is unknown, Student t-distribution can be used to find a confidence interval on the mean. Modeling of OD matrix can be summarized in the following steps:

1. Start with an initial OD matrix M.
2. Run the simulation model with matrix M for n number of seeds.
3. Construct a 95% confidence interval on the traffic count at location i, $\bar{x}_i \pm t_{0.95}\sqrt{S_i^2/n}$, where $\bar{x}$ is the average of traffic counts and S_i^2 is the sample variance at location i.
4. If the confidence interval covers the observed count μ_i at location I stop. Otherwise update matrix M and go to step *1*.

After each simulation run, the traffic counts at these eleven locations are obtained. The OD matrix is updated until the 95% confidence interval of the traffic volume at each location covers the observed traffic count.

Modeling of Inter-arrival Times

Because of its operational design, the operational efficiency of the circle is closely related to the inter-arrival times of vehicles on route 33 westbound, route 34 northbound and route 33/34 eastbound, as well as the gap acceptance/rejection of vehicles at locations 4 and 5. Clearly if the inter-arrival times of vehicles at 34 northbound and 33 westbound are increased, vehicles at location 4 and 5, respectively, will have difficulty in finding acceptable gaps to continue. Hence, it is important to run the simulation using correct inter-arrival times and gap acceptance/rejection distributions to develop a reliable model.

The shape of the histogram plotted using the inter-arrival data resembles very much that of an exponential probability distribution, but with a rather longer tail. Chi-square and Kolmogorov-Smirnoff tests were used to test the goodness-of-fit of the data; however, the H_o hypothesis was rejected at 10% level of significance. It was then realized that the inter-arrival times of vehicle approaching the circle were largely affected by the two traffic signals located in the vicinity of the circle. Vehicles arrive at the circle in batches and in certain order, as a result of the synchronization effects of these upstream signals. The synchronization of these signals had been designed so that two major flows, route 33 westbound and route 34 northbound traffic streams miss each other. This creates more acceptable gaps for vehicles and which is also more consistent with real world operations (See Figure 2).

The signal timing plans of the two signalized intersections were coded by using actuated signals feature in PARAMICS. The before and after circle models were then revised by incorporating these actuated signal plans. In the revised version of the model, interarrival times are treated as output variables, rather than input variables because the input modeling is taken care of by the traffic signal timings in the model. A

95% confidence interval with a relative error of 5% constructed for the inter-arrival times of vehicles covers the observed average inter-arrival time for the two major flows (*Note*: If one hundred, 95% confidence intervals, with a relative error of 5% were constructed, a relative error of at most 5% with respect to the unknown real mean (μ), in approximately 95 out of 100 cases is expected. In the remaining 5 cases, the relative error of the estimate would be greater than 5%). Because the inter arrival data do not fit to any probability distributions, instead of an input variable, the data are treated as an output variable.

Modeling of Gap Rejection

Table 6 shows the results of statistical analysis using the gap rejection data. Analysis shows that vehicles' gap rejection times follow a negative exponential probability distribution function. It is assumed that gap acceptance/rejection times of individual vehicles are independent.

Table 6. Chi-Square test of gap rejection data

Location	χ^2 (Observed)	$\chi^2_{k-1,0.90}$	Remark
1	11.932	14.684	H_0 accepted
2	5.939	14.684	H_0 accepted
4	7.680	14.684	H_0 accepted
5	4.724	14.684	H_0 accepted

PARAMICS API option enables users to simulate the developed gap rejection model. At each time step if the vehicle is within the link that has a yield sign (such as locations 2, 4 or 5) or a stop sign (location 1) it checks the approach link associated with that sign. PARAMICS API then detects the leading vehicle on the approach link and calculates the approximate time, t_A, it would take to arrive to that location. Using the inverse of the gap rejection distribution a critical value t_C is assigned randomly to each vehicle looking for gap acceptance, regardless of vehicle characteristics. If $t_A < t_C$, the vehicle rejects the gap.

Without the gap rejection model developed using API, PARAMICS's default gap rejection model does not yield realistic entry wait times. Without a location specific gap rejection model it is not possible to model the circle accurately, because the capacity of the circle is closely related to vehicle's gap rejection times.

Driver characteristics are expected to affect the model considerably. However, it is not possible to gather such extensive individual level data. Thus, during the calibration process aggressiveness, awareness and familiarity of vehicles were modified to be able to obtain simulation outputs close to observed system outputs. This kind of calibration is needed because of the lack of individual driver data as explained in section 2.

Results

Collingwood Circle has a rather unusual operational design. It is well known that in modern roundabouts, the circulating traffic has the right-of-way. However, traffic flow on route 33 westbound, route 34 northbound and route 33/34 eastbound have the priority over the traffic circulating in Collingwood Circle. During the morning rush hour, traffic flows heavily on route 34 northbound. Since route 33 westbound has priority over this traffic flow, the circle experiences a queue backup before the yield sign at location 5, which blocks the circulating traffic coming from route 33/34 eastbound and waiting for acceptable gaps at location 4. Moreover, the queue backup before location 4 blocks the traffic flow to route 34 southbound.

Average wait times at locations 4 and 5 and average interarrival times on route 34 northbound and route 33 westbound in Figure 2 are used in objective validation tests, after all the majority of the traffic is heavily located at these points both during morning and afternoon rush hours. The model is simulated with independent replications until model outputs attain a confidence level of 95% with a relative error of 5% for both locations. As explained previously, because the probability distribution of the output variables is not known, using the central limit theorem it is assumed that the sampling distributions of the population means are approximately normal with unknown variances. Student *t*-distribution is used to construct the 95% confidence interval for the population mean. Table 7 and Table 8 present the simulated and observed system outputs. From these results, it can be asserted that most of the average wait time values are in a statistically valid range for this set of system data. Table 7 and Table 8 also show the simulated and observed average inter-arrival times. These values also are close to the observed data, indicating that the simulation model is statistically valid.

Table 7. Simulated and observed system data between 7 a.m. and 9 a.m.

Location	Average Wait Time (sec)		Average Inter Arrival Time (sec)	
	Simulated	**Observed**	**Simulated**	**Observed**
Rt. 33 Westbound (5)	[2.01, 2.45]	2.51	[3.22, 3.39]	3.42
Rt. 34 Northbound (4)	[6.08, 6.94]	6.2	[2.59, 2.69]	2.6

Note: The numbers in the parentheses denote the location number in Figure 2 for the average wait time results.

Table 8. Simulated and observed system data between 3 p.m. and 5 p.m.

Location	Average Wait Time (sec)		Average Inter Arrival Time (sec)	
	Simulated	Observed	Simulated	Observed
Rt. 33 Westbound (5)	[2.29, 2.61]	2.34	[4.23, 4.33]	4.37
Rt. 34 Northbound (4)	[2.53, 2.86]	2.26	[5.12, 5.24]	5.47
Rt. 33/34 East Bound (2)	[9.61, 11.87]	10.33	[1.95, 1.99]	1.98
CR-547 West (1)	[11.55, 13.92]	13.86		

Note: The numbers in the parentheses denote the location number in Figure 2 for the average wait time results.

Table 9 shows the average network travel time for the current and proposed designs of Collingwood circle. Average network travel time is simply the sum of travel times of all vehicles in the network during the peak period divided by the total number of vehicles. This output measure is employed because the average network travel time provides a better overall mobility measure than other output measures. It is determined that the travel times of vehicles in the current and proposed designs of the circle do not differ significantly. Therefore, the proposed design of the circle will not adversely affect the mobility in the network.

Table 9. Average network travel time results

	AM Period	PM Period
CURRENT DESIGN	[171.6, 176.7] seconds	[169.5, 174.7] seconds
PROPOSED DESIGN	[169.1, 172.5]	[167.9, 171.1]

Although independent sets of observed system data would yield statistically more valid models, it is a meticulous process to gather and extract even one day of system data. Improved model validation with multiple system data is left as future work.

Sensitivity Analysis

Sensitivity analysis is a useful tool for determining whether the simulation output varies significantly when the value of an input parameter is changed or the input probability distribution is changed. If the output is sensitive to minor changes to the input, the model should be revised accordingly.

In experimental design, the input parameters are called factors, and the output performance measures are called responses [6]. A 2^k factorial design test is used in this study to assess the stability of the developed model.

Suppose that there are *k* factors and the effect of each factor on the selected output measure needs to be estimated. 2^k factorial design requires choosing just two levels for each factor and then determining the effect of each level on the selected response while fixing the level of other factors. Detailed information on the subject is given in [6] as well as in the Appendix. For each factorial combination independent simulation runs should be performed to construct a confidence interval for the response value. In the sensitivity analysis here, a 95% confidence level and a 5% relative error are assumed.

As mentioned before, the efficiency of the circle is closely related to the gap rejection of vehicles at locations 4 and 5. It is important to observe whether the model is sensitive to the *mean* of the exponential gap rejection probability distribution and also the target

mean reaction time of vehicles based on the change in the average network travel time (response). Table 10 and
Table 11 show the levels of each input factor and the response values for the current design at morning and afternoon peak periods, respectively. 95% confidence interval with a relative error of 5% for the morning peak response value is [172.6, 176.2 seconds] and for the afternoon peak is [171.4, 172. 4 seconds].

It is thus observed that the response does not vary drastically with minor changes in the gap rejection model and the target mean reaction time of vehicles. This proves that the model remains stable with respect to minor changes in the input.

For the proposed model, sensitivity analysis is also a very useful validation tool, because system behavior is indefinite due to unavailability of after-construction system data. If the data were available, there would not be any need for the development of a simulation model. In this case, it is assumed that the OD demand patterns and the inter-arrival times will remain the same after the implementation of the proposed model. However, the gap rejection model will change. It is assumed that the gap rejection data will still follow an exponential probability distribution, but with different minimum critical gap values because the traffic speed in the circle will decrease as a result of reduce curvature. Reduced speed of the circulating traffic will certainly change the minimum critical gap values of vehicles waiting to enter the circle.

Table 10. Design matrix for a 2^3 factorial design – current design a.m. period

Factor Combination	33	34	Reaction Time	Average Network Travel Time
1	+	+	+	177.52 seconds
2	+	-	+	176.32
3	-	+	+	174.78
4	-	-	+	171.75
5	+	+	-	176.05
6	+	-	-	173.73
7	-	+	-	173.75
8	-	-	-	171.28

Table 11. Design Matrix for a 2^3 factorial design – current design p.m. period

Factor Combination	33	34	Reaction Time	Average Network Travel Time
1	+	+	+	171.28 seconds
2	+	-	+	171.48
3	-	+	+	171.76
4	-	-	+	172.1
5	+	+	-	173.24
6	+	-	-	171.54
7	-	+	-	172.16
8	-	-	-	171.54

In the proposed model the levels of the input parameters are kept far apart to observe the variation in the response. Two level effect of gap rejection at location 1, location 4 and location 5 in Figure 3, as well as the target mean reaction time of vehicles were analyzed. Table 12 and Table 13 show the levels of each input factor and the response values for the proposed design at morning and afternoon peak periods, respectively. For a 95% confidence interval with a relative error of 5% for the morning peak response, the value of the proposed design is [170.9, 175.1] seconds, and for the afternoon peak is [171.5, 183.2] seconds.

Table 12. 2^4 factorial design matrix for the proposed design a.m. period

Factor Combination	33	34	33/34	Reaction Time	Average Network Travel Time
1	+	+	+	+	178.26 seconds
2	+	+	-	+	175.08
3	+	-	+	+	176.17
4	+	-	-	+	174.38
5	-	+	+	+	179.66
6	-	+	-	+	180.50
7	-	-	+	+	173.33
8	-	-	-	+	173.70
9	+	+	+	-	169.90
10	+	+	-	-	170.18
11	+	-	+	-	168.72
12	+	-	-	-	169.22
13	-	+	+	-	170.10
14	-	+	-	-	168.94
15	-	-	+	-	169.20
16	-	-	-	-	168.77

Table 13. 2^4 factorial design matrix for the proposed design p.m. period

Factor Combination	33	34	33/34	Reaction Time	Average Network Travel Time
1	+	+	+	+	187.20 seconds
2	+	+	-	+	195.31
3	+	-	+	+	178.08
4	+	-	-	+	183.35
5	-	+	+	+	196.1
6	-	+	-	+	189.49
7	-	-	+	+	182.34
8	-	-	-	+	184.03
9	+	+	+	-	167.82
10	+	+	-	-	169.22
11	+	-	+	-	167.38
12	+	-	-	-	165.90
13	-	+	+	-	169.38
14	-	+	-	-	168.60
15	-	-	+	-	166.46
16	-	-	-	-	166.38

Route 33 / 34 eastbound carries a heavy traffic volume in the afternoon peak, which is practically the total traffic volume on route 34 northbound and route 33 eastbound in the morning on the reverse route. In the proposed design this heavy traffic is forced to slow down before the yield sign at location 1. When the target mean reaction time or the mean of the gap rejection distribution at this location is increased, the system experiences long queue backups before location 1. This explains the great variation in the sensitivity analysis results of the proposed design during the afternoon peak period.

Cost Benefit Analysis (CBA)

Since the proposed design of the circle does not improve mobility at the circle, the conditions should be determined under which this construction project could be financially viable. CBA is the most commonly used approach in evaluating highway transportation projects. It requires the quantification and comparison of the various benefits and costs generated by a project. The effects from the project are first enumerated and classified as costs and benefits. Then, an attempt is made to quantify each effect and express it in monetary terms using appropriate conversion factors [(2)]. Major steps in CBA process are [(5)]:

- Define base case and alternatives.
- Set analysis period.
- Analyze traffic effects.
- Estimate benefits and costs relative to base case.
- Evaluate risks.
- Rank alternatives.

In this study, the base case is a do-nothing option (also called do-minimal), which represents the continued operation of the current facility without major investments. The alternative option is the improved design of the circle as decided by NJDOT.

Benefits of the alternatives are analyzed by using the calibrated simulation model developed in PARAMICS. However, because the proposed design is not in use, the simulation model will be a representation of the proposed facility too. While it is possible to capture the current operation of the facility using the available real-world data, simulation of the proposed design is based on assumptions on some key parameters such as gap acceptance/rejection parameters, inter-arrival times of vehicles, and traffic demand levels. A range of these parameters is utilized in the analyses to evaluate risks in estimating costs and benefits.

The identification of costs and benefits requires a complicated analysis because of the multidimensional impacts of a given transportation investment. The most important effect of a transportation investment is the desired improvements regarding the accessibility conditions, more specifically improvements of travel conditions. There are however several other impacts of transportation projects. For example, highway transportation offers direct benefits to businesses (i.e. trade, manufacturing, agriculture and tourism), and indirectly generates economic growth as clearly shown in [9].

In this study, only the direct effects of the project on travel and safety conditions are considered whereas the changes in externalities, land use, economic growth and in investment multiplier are neglected. These effects are monetarized in the following cost categories.

Vehicle operations

Vehicle operating costs are directly borne by drivers. They include fuel and oil consumption, expected and unexpected maintenance; wear and tear, insurance, parking fees and tolls, and automobile depreciation. All of these costs can be expressed as a function of annual mileage traveled for the given make and age of the vehicle.

Congestion

Congestion cost defined here as the time-loss caused by traffic conditions and drivers' discomfort, both of which are a function of increasing volume to capacity ratios. Time loss can be determined through the use of a travel time function. Its value depends on the distance between any OD pairs (d), traffic volume (Q) and roadway capacity (C). Although drivers are not homogeneous with respect to their value of time, to calculate congestion costs, an average value of time (VOT) (in dollar per hour) should be employed.

Accident

Accident costs include the cost incurred due to different types of accidents. These include both the cost of property damage, medical treatment in the case of injuries, the pain of suffering experienced and the loss of productivity resulting from fatalities.

Capital

Infrastructure costs include all long-term expenditures, such as land acquisition costs; cost of facility construction, material, labor and administration costs, regular and unexpected maintenance expenses. These costs are also subjected to an interest rate over the lifetime of the facility. Maintenance cost is disregarded in the analyses because both alternatives bear this cost element.

Air Pollution

The consequences of air pollution are pervasive and far-reaching, tracking of its effects is complex. Air pollution costs are usually estimated by multiplying the amount of pollutant emitted from vehicles by the unit cost values of each pollutant.

Noise Costs

The costs of noise externalities are most commonly estimated as the depreciation in the value of residential units alongside the highways. Presumably, the closer a house is to the highway, the more its value will depreciate.

The major benefits of the proposed design of Collingwood Circle are expected to result from the reductions in congestion and accident costs. Direct costs, on the other hand, are initial investment costs. A net-present value comparison requires having the values of these costs and benefits at different points in the projected lifetime of the project. Using a discount rate, these costs and benefits can be shifted back in the present time, and the project can be evaluated using the estimated net-present value.

When evaluating various investment projects, whether in transportation or in any other business, the analysts can assign different weights of importance on each cost and benefit. In other words, objectives are usually weighted to reflect their relative importance to the analysts or the decision-maker.

The Goal Achievement Matrix (GAM) method is commonly used when ranking different alternatives, where the outcomes of each alternative are scored using a common and uniform scale and the best alternative is selected using the relative weights of each outcome. Scoring under a uniform scale is a necessary method for the evaluation of different alternatives where a mixture of different scales e.g. monetary values, vehicle counts, construction period is present.

The GAM method is used to evaluate the current and proposed designs of Collingwood Circle. For this purpose, the weights of importance need to be assumed for the outcomes of each alternative. Because the assumed weights can affect the evaluation results, a set of weights is assumed for each criterion to understand how the results vary for different assumptions. Finally, construction period should also be selected as a criterion in evaluating the two alternatives. Throughout construction period drivers will incur delays as a result of limited roadway capacity that will adversely affect the benefits of the project (In construction period criterion, the do-nothing alternative is assigned with a very small time period to normalize the score). Table 14 shows the expected criteria of the evaluation analyses and

Table 15 shows the assumed set of weights for each criterion.

Table 14. Decision criteria and units

Criteria	**Variable**	**Units**
1. N.P.V. of Investment	Capital	$
2. Mobility	Network Time	seconds
3. Safety	Accidents	$
4. Construction Period		months

Table 15. Weights of importance for each criterion

Weights					
Criteria	1	2	3	4	5
1	0.08	0.10	0.05	0.05	0.0
2	0.45	0.50	0.35	0.55	0.50
3	0.45	0.40	0.55	0.35	0.50
4	0.02	0.0	0.05	0.05	0.00
Total	1.00	1.00	1.00	1.00	1.00

The score of each criterion is gathered using simulation results of each alternative. The scores shown in Table 14 are in different scales. They are normalized using the approach where the best score for each criterion is defined as 100. The scoring is repeated and the total normalized scores are obtained for each criterion. These are normalized once again, and multiplied by their relative weights of importance. The alternative that yields the maximum score is then selected as the better alternative.

When evaluating projects, the decision maker should always take uncertainty into account. The term uncertainty is used to indicate the degree of inaccuracy associated with the estimation of the project's future costs and benefits [(2)]. Uncertainty might appear in the estimation of the construction period, capital costs, and the level of traffic demand. When evaluating two alternatives where the second alternative is do-nothing, the net present value of construction costs, and the length of construction period do not affect the results significantly. After all the major advantages of the do-nothing alternative are already the considerably low investment amount and the nonexistence of the construction period. Therefore, the effect of using various sets of weights under different demand levels should be analyzed as well. Utilizing different demand levels represent the uncertainty of traffic demand in the analyses.

Analysis

As mentioned before, the expected benefits of the proposed design of the facility is the increased safety. However, as reported in the simulation results, the proposed design of the facility does not significantly change the travel time in the network. However, the important question is whether the proposed design can better handle the increased traffic volumes over the next, say, five or ten years.

To estimate the performance of the proposed geometric and operational design of Collingwood Circle, the demand levels at crucial locations in the network are increased by an annual traffic growth rate of 1.5%. It is not realistic to assume that the demand levels will increase proportionally between each OD pair in the network. Only the major traffic volume along route 33, route 34 and route 33/34 are increased by 1.5%. The simulation analysis for the morning and afternoon peak period show that the current geometric and operational design of the circle can handle increased traffic demand levels for another 6 years for both periods (The increase in demand level at the 6^{th} year corresponds to 9-10% at the selected locations). The cut-off year is found out as the 6^{th}

year, where the average network travel time is between [187.4, 266.5] seconds. After the sixth year, the simulation runs show that the system cannot handle the traffic load. This leads to a traffic lock-up for various seed values. However, it should be noted that this might not reflect the actual operational efficiency of the circle under increased loads. First, the vehicles' driving behavior changes as the delays increase. The average network delay result given above does not consider the change in drivers' gap acceptance/rejection behavior. Second, drivers often seek alternative routes when the first route gets congested. Third, there are many other driver characteristics that a simulation model cannot account for. These characteristics can greatly influence the traffic lock-ups (i.e., sharing lanes, increased reactions and headway times). Therefore, it is a very meticulous task to determine exactly the impacts of the expected growth in traffic; however, a simple simulation analysis with increased demand presents a lower bound value for the lifetime of the current operational and geometric design of this circle.

A similar analysis is carried out using the simulation model of the proposed circle design. The analysis shows that the average network travel time is between [178.4, 199.2] seconds at the fifth year, and between [188.3, 231.9] seconds at the tenth year. Clearly, the proposed design can better handle traffic volumes as a result of the "yield-at-entry" rule, which prevents lock-ups.

Assuming an analysis period of ten years and an annual interest rate of 3.5%, the mobility costs calculated for every year can be shifted back to present time using the following formula:

$NPV = \frac{R}{(i+1)^n}$ where, *NPV* is net present value ($), *R* is annual cost ($), *i* is interest rate (%) and *n* is the analysis period (years).

Assuming a value of time $12 per hour, the present cost of congestion for the current design and the proposed design is estimated as $132 million and $125 million, respectively. The estimated travel time-savings with the proposed design is approximately $7 million over ten years.

To calculate the benefits of the proposed design resulting from the increased safety, accident costs need to be calculated. The reduction in the number of accidents appears as a benefit in the CBA.

Between the years 2001 and 2002, 62 accidents were reported at Collingwood Circle. There were 26 sideswipe, 14 rear end, 18 angle and 4 fixed object accidents. Of these accidents, 11 led to minor injuries. Unit accident costs are adopted from [(8)]. Using the costs figures an approximate cost of $2 million is calculated for 2001 and 2002. Assuming a constant accident rate at the circle, the net present value of this cost is approximately $9.35 million over ten years.

The safety analysis of the Collingwood Circle based on the simulation results shows that the change in crash rates highly varies based on different empirical equations. Based on the Maycock and Hall approach, the analysis shows an increase in crash rates by 67%, mainly as a result of increased rear-end accident. On the other hand, based on Arndt approach, the analysis shows 39% reduction in the accident rates. Therefore, there is not a clear-cut conclusion of the effect of the proposed design on safety at Collingwood Circle.

The monetary analysis of the Collingwood Circle based on an assumed reduction in the number of accidents by 30% over ten years would result in a net present value of $8.0 million in accident cost. This figure is based on the assumption that with the current design of the circle the accident cost is $1 million dollar per year (based on the accident statistics for 2001-2002 and the accident unit costs given in [(7)]. Thus the net present benefit is $1.35 million. Following the first weight set given in
Table 15, the total and weighted normalized score matrices can be constructed as in Table 16 (The capital cost of the project is reported as $800,000 by the NJDOT officials. In normalizing the score a minimum value of 1 is selected for analysis purposes). Note

that the mobility and safety scores are based on the estimated congestion cost savings of $7 million and $1.35 million over ten years as explained above. Based on these assumptions the proposed design has approximately the same score that of the do-nothing option.

Table 16. Total and weighted normalized score matrices

		Total Normalized Score		**Weighted Normalized Score**	
	Weight	**Proposed**	**Do-Nothing**	**Proposed**	**Do-Nothing**
1. Net Present Value	0.08	1.0	100.0	0.08	8.0
2. Mobility	0.45	100.0	95.0	45.0	42.75
3. Safety	0.45	100.0	84.7	45.0	38.1
4. Construction Period	0.02	0.3	100.0	0.006	2.0
				TOTAL 90.10	**90.75**

If the CBA is based solely on the net present value of the costs and benefits, the conclusion is highly discrepant. The net present value of the safety benefits is $1.35 million assuming a 30% reduction in the number of accidents. Also, the net estimated savings of reduced congestion is approximately $7 million. Thus the total benefits of enhanced safety and mobility is approximately $8.35 million and the capital cost of the project is $800 thousand. Based on the net present value comparison only, the proposed design is a more favorable option.

As a final note, based on the net present value comparison, the proposed design is still a favorable option even when the accident rate increases over years. Specifically, the net present value of accidents is estimated as $12.1 million assuming an increase of 65% over ten years as estimated by Maycock and Hall approach. The increase in accident costs in this scenario is $2.7 million with respect to the do-nothing option.

However, the estimated benefits by enhanced mobility, namely $7 million, still outweighs this increase in accident cost.

Brooklawn Circle

The Brooklawn Circle is located at the intersection of route 130 and route 47 in Camden County in New Jersey. Besides these major routes, several other roads converge, making this circle a cross point of the north-sound corridor in southern NJ. The Brooklawn Circle includes two circles as shown in Figure 5. Route 130, route 47, Creek road, and Hannevig Avenue intersect at the east circle. West circle is the extension of east circle, where route 130 negotiates through both circles. New Broadway Avenue and route 130 intersect at the West circle.

Figure 5. Aerial photo of the Brooklawn Circle

At the north of the east circle, route 130 south carries traffic with three lanes, and reduces to two lanes 1000 ft before the circle. The speed limit on route 130 SB is 45 miles per hour. A concrete island helps to channel traffic into the circle, where route 130 merges into the circle. Route 130 exits the east circle and connects to the west circle by means of a two-lane roadway, with one lane in each direction.

Another leg entering the east circle is route 47. This route originates from this circle and extends to south carrying two lanes of traffic. Traffic at the intersection of route 47 and the east circle is impacted by the Creek road. Creek road has lane in each direction, and it does not actually intersect the circle but intersects route 47. The left turns to Creek road from the east circle affects the through traffic originating from the circle and headed to route 47 SB. This not only causes congestion in the east circle, but also leads to accidents.

Neither circle has a common operational design. Priority movements in the circles do not follow modern roundabout operational restrictions. For example, only route 130 NB approaching the east circle at location 1 yields the circulating traffic. At other locations, circulating traffic yields to the approach traffic (See Figure 5).

Motor vehicle crash reports were collected for a three-year period (1998 – 2000) from the Brooklawn Borough Police Department. In the east circle there were 334 accidents total, and 43 of which were injury accidents. As shown in Table 17, around 58% of all the accidents were same direction sideswipes and fixed object accidents. These figures show that most of the accidents were due to the negligence of drivers of the concrete islands that are used for channelization, and due to weaving movements within the circle.

Table 17. East Circle Accident Summary [4]

	Accidents	Injuries	Side-swipe	Rear End	Concrete Island	Angle	Misc.
1998	123	21	37	35	26	19	6
1999	112	12	35	30	21	18	8
2000	99	10	32	26	26	12	3
Total	**334**	**43**	**104**	**91**	**73**	**49**	**17**

Table 18 shows the accident history in the west circle within the same time period (1998 - 2000). There were only 13 accidents during the three years. The same cause of accidents can be observed in the west circle.

Table 18. West circle accident summary [(4)]

	Accidents	Injuries	Side-swipe	Rear End	Angle	Misc.
1998	14	2	3	5	5	1
1999	12	2	7	2	2	1
2000	19	7	7	5	6	1
Total	**45**	**11**	**17**	**12**	**13**	**3**

Table 19. Traffic volumes in 2000 [(4)]

	Direction	Location	AADT
Route 130	Southbound	East circle	15,216
Route 130	Northbound	East circle	12,913
Hannevig Avenue	Southbound	East circle	986
Hannevig Avenue	Northbound	East circle	916
Route 130	Southbound	E & W circles	14,184
Route 130	Northbound	E & W circles	11,769
Route 47	Southbound	East circle	8,630
Route 47	Northbound	East circle	8,558
Creek Road	Southbound	East circle	2,850
Creek Road	Northbound	East circle	4,160
New Broadway Road	Southbound	West circle	8,016
New Broadway Road	Northbound	West circle	5,977
Route 130	Southbound	West circle	11,584
Route 130	Northbound	West circle	9,032

Table 19 shows that the majority of traffic is carried by route 130, Route 47 and New Broadway road. During the morning peak period, the traffic flows northbound on route 130 at the East circle. During the afternoon peak period, the traffic regime is the opposite. Long queue formations at route 130 southbound at the east circle were observed.

The demographics study conducted by Dellaware Valley Regional Planning Commission (DVRPC) [4] showed that there is an expected reduction in the future traffic volumes of the Brooklawn circle. This estimation was based on the forecasted employment in the municipalities nearby the Brooklawn circle. Traffic demand projections for the future years were estimated by the regional travel simulation model of DVRPC. Based on this finding, DVRPC study [4] concluded that the congestion level analysis of the facility with the future demand levels was unnecessary.

The issues and concerns of the local officials can be listed as follows:

- High frequency of accidents in/around the circle.
- Cut-through traffic adds unwanted traffic to residential streets.
- Maintaining access to the two undeveloped parcels to NB side of route 47 between Creek Road and Big Timber Creek for economic viability.
- Left turn from route 47 SB to Creek Road.
- Severe afternoon congestion on route 130 SB and morning congestion route 130 NB.

There are six mid-range proposed alternatives to the current operational design of Brooklawn Circle in the DVRPC report [4]. Alternative 2B is selected by the NJDOT officials as the proposed alternative (See Figure 6). The left turns from route 47 SB to Creek Road not only blocks through movement on route 47 SB, but also is problematic due to numerous accidents that were observed at this point. As shown in Figure 6, Alternative 2B eliminates the left turns to Creek Road by a new median barrier along route 47 and the right turns from Creek Road into the circle, and right turns from route 47 to Creek Road would continue. Traffic between Creek Road and route 130 would use an improved Old Salem Road. A median break and a traffic signal on route 130 at Old Salem Road / Nansen Avenue intersection would permit access from Creek Road / Old Salem Road to route 130 SB. A concrete island on Nansen Avenue would permit right turns in and right turns out from / to route 130 SB, while preventing through traffic from Old Salem Road in to Nansen Avenue [4].

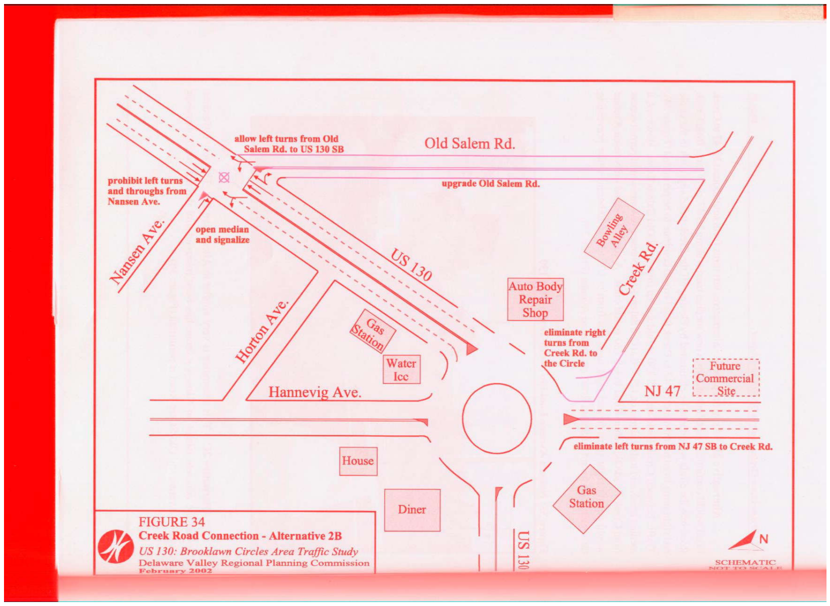

Figure 6. Alternative 2B – Creek road connection [4]

Figure 7 shows the simulation model of the circle developed in PARAMICS in 2-D and 3-D views.

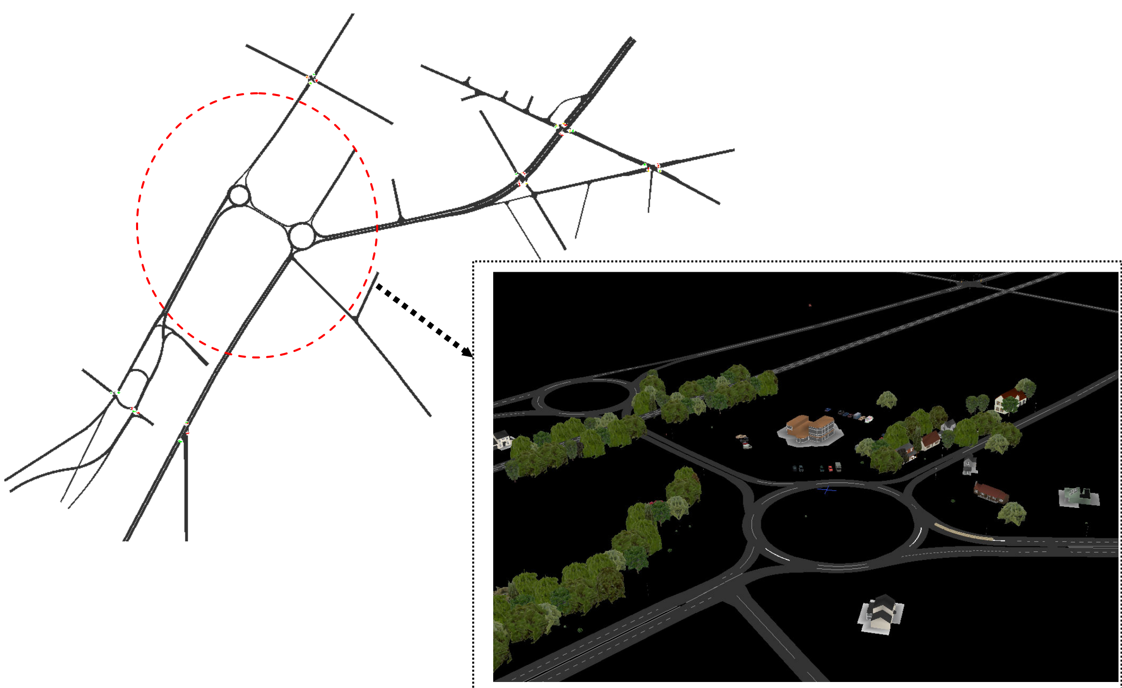

Figure 7. Brooklawn simulation model developed in PARAMICS

The simulation model of the Brooklawn Circle in PARAMICS consists of 153 nodes and 166 links, and 19 demand zones.

Model Verification

The simulation model of the Brooklawn Circle was run at varying levels of traffic volumes and using different random number streams to observe whether vehicles behave reasonably (i.e. correct turns, accepting priority movements at junctions, proper lane changing, and using correct lanes while exiting the roadway). This step is crucial for detecting any obvious errors in the model.

Description of Data

Traffic data were collected at the circle on 21 April 2004 from 7 a.m. to 5 p.m. The POGO (See Figure 4) was located at the east circle with cameras directed at each of the four approaches. The portable mast with a Sony camcorder and an omni-directional camera were located at the west circle. The recorded traffic data were then extracted in Rutgers Intelligent Transportation Systems Laboratory. The extracted data include (1) vehicle counts at 21 locations at every hour, (2) vehicle inter-arrival times at 6 locations, (3) vehicle wait time before yield signs at 6 locations, and (4) gap acceptance/rejection times at 5 of 6 yield signs.

Model Validation and Calibration Efforts

The model validation process is twofold: subjective tests (face validation) and objective tests. The simulation models of the current and the proposed design of the circle were demonstrated to NJDOT officials during several project meetings. The collected and extracted ground-truth data were used in the objective tests. The ground-truth data involved one-day of real-world system data. A thorough objective test requires a set of real system data to statistically compare the simulation and ground-truth data. However, collecting and extracting the data set of a single day is a very long and costly process. As it was postulated in the statistical analysis of Collingwood Circle, if the confidence interval of a given output variable built by the simulation data covers the observed level of the output variable, then the simulation model can be assumed to be valid.

Modeling of Origin – Destination Matrices

The same procedure conducted for the Collingwood Circle is followed for the Brooklawn Circle. The OD demand matrix is generated based on twenty-seven locations by trial and error method[1].

Modeling of Inter-arrival Times

The inter-arrival of vehicles at the circle approaches is affected by the traffic signal timings near the facility. There are six traffic signals in the vicinity of the east and west circles that regulate the traffic going to the circle. The locations of these traffic signals are shown in Figure 8.

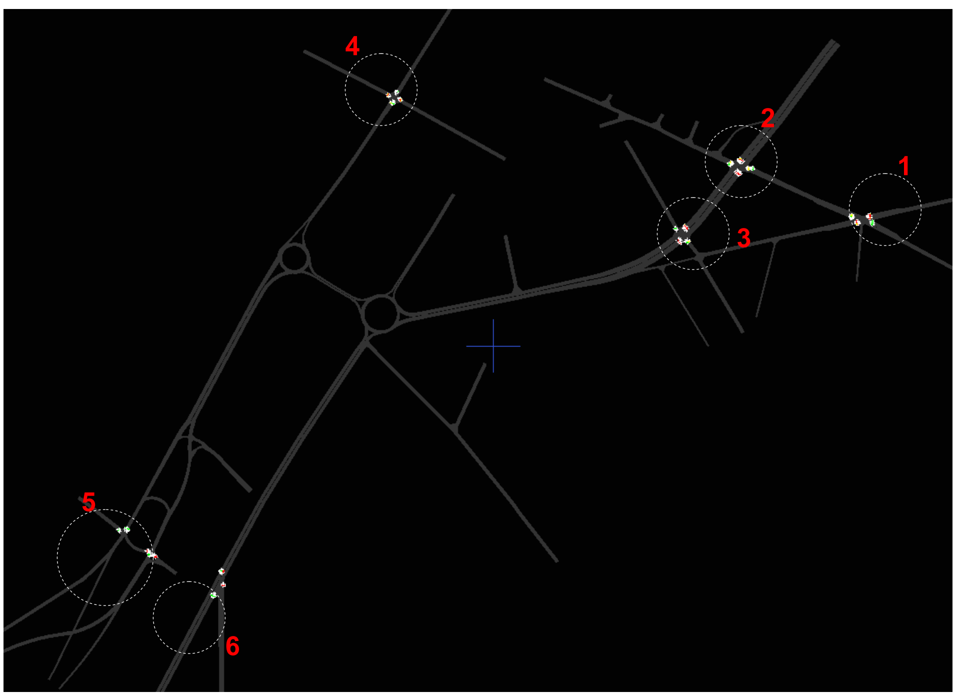

Figure 8. Locations of traffic signals around Brooklawn circle

[1] In addition to the 21 locations where the ground-truth data were collected and extracted, NJDOT provided turn counts at 6 traffic signals nearby the circle

The signal timing plans of these signalized intersections were provided by the NJDOT and were coded using the actuated signals feature in PARAMICS. The inter-arrival time comparison of the ground-truth data and the simulated data are presented in the validation results section.

Modeling of Gap Rejection

As mentioned previously, the default gap rejection model of PARAMICS does not yield realistic entry wait times. Without a location specific gap rejection model, it is not possible to model the circle accurately, because the capacity of the circle is closely related to vehicle's gap rejection times. The API feature of PARAMICS was used to model the gap rejection behavior of vehicles at the Brooklawn Circle. Gap rejection data were extracted at locations 1-5.[2]

The histogram of gap rejection data at Brooklawn Circle reveals that the gap rejection data of vehicles follow either lognormal or Weibull distribution. It is reasonable to assume that as the approach speed decreases, vehicles at the yield signs accept smaller gaps. This could be attributed to the fact that at lower approach speeds, drivers do not consider themselves at risk when merging the traffic circle. Figure 9 shows the histogram of gap rejection data for the inner and outer lanes at location 2. As the approach speed increases, the minimum accepted gap increases as shown in the figure. In the gap rejection data of the Collingwood Circle for example, as the minimum accepted time line (Figure 9) increases, the gap rejection histogram follows the tail shape of lognormal distribution, which can be approximated as a negative exponential distribution.

[2] Since the vehicle queue due to the yield sign at location 1 usually causes blockage at location 6, the gap rejection data was not possible at location 6.

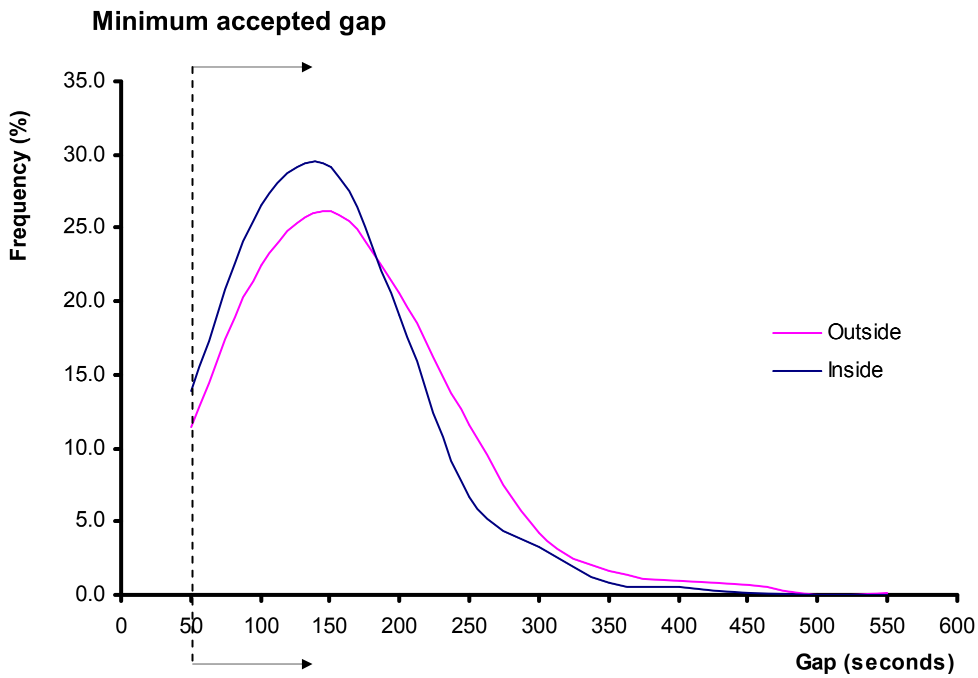

Figure 9. Histogram of gap rejection data at location 2

Chi-square goodness-of-fit tests were performed to decide whether the gap rejection of vehicles follows a negative exponential probability distribution.

Table 20 shows the Chi-square test results and the probability distribution parameters for these locations.

Table 20. Chi-Square test of gap rejection data

Location	χ^2 (Observed)	$\chi^2_{k-1,0.90}$	Remark	Parameters
1	7.365	14.684	H_0 accepted	$\alpha = 1.82$, $\beta =$ 0.798
2	13.50 8.625	14.684	H_0 accepted	$\alpha_1 = 1.81$, $\beta_1 =$ 0.561 $\alpha_2 = 1.59$, $\beta_2 = 0.492$
3	4.33 4.48	14.684	H_0 accepted	$\alpha_1 = 1.54$, $\beta_1 =$ 0.972 $\alpha_2 = 1.59$, $\beta_2 = 0.797$
4	13.47	14.684	H_0 accepted	$\alpha = 2.50$, $\beta =$ 0.6546
5	14.29	14.684	H_0 accepted	$\alpha = 2.52$, $\beta =$ 0.6104

Note: α is the shift parameter (subscript 1 and 2 stand for outside and inside lanes, respectively. β is the sample mean of the data set.

Using the negative exponential probability distribution as the gap rejection of vehicles at the selected yield signs, the PARAMICS API was used to simulate the gap rejection behavior. The gap acceptance/ rejection logic was presented in the simulation analysis of the Collingwood Circle. Regarding location 6, the gap rejection model of location 5 is adopted.

Results

The Brooklawn Circlet too has an unusual operational design. Although geometrically the East and the West circles resemble a modern roundabout design more so than the Collingwood Circle design, the prioritization of traffic is not standard to roundabouts. The heavy traffic on route 130 SB direction during the afternoon peak period causes long queues due to the weaving within the circle and the reduced speed at the circle entrance. Location 1 causes queue backups both during morning and afternoon peak. Morning peak queues are due to the high demand headed to route 130 NB. On the other hand, afternoon peak queues are due to the low inter-arrival time at location 1 approach, which restricts available gaps for the vehicles waiting at the yield sign.

Average wait time at yield signs and the inter-arrival times are the main variables that define the capacity of the traffic circle. As in the validation of the Collingwood circle simulation model, these variables were utilized in validating the simulation model of the Brooklawn circle. Table 21 and
Table 22 show the actual values of these variables, and the confidence interval obtained by the simulation model for morning and afternoon peak periods, respectively. The simulation model was run with independent replications until model outputs attained a confidence level of 95% with a relative error of 5% for 6 of the selected locations (See Figure 5). As explained previously, a prior knowledge of the probability distribution of the selected output variables was not available. Therefore, using the central limit theorem the sampling distributions of the population means were assumed approximately normal with unknown variances. Student *t*-distribution was used to construct a 95% confidence interval for the population mean.

Table 21. Simulated and observed system data between 7 a.m. and 9 a.m.

	Location	Average Wait Time		Average Inter Arrival Time	
		Simulated	**Observed**	**Simulated**	**Observed**
	1	[0.98, 1.08]	1.13	[15.13, 15.83]	15.24
	2	[1.57, 1.72]	1.58	[5.20, 5.36]	5.27
1st Hour	**3**	[2.92, 3.10]	3.08	[2.75, 2.81]	2.78
	4	[2.19, 2.41]	2.12	[5.23, 5.52]	5.39
	5	[3.60, 3.85]	3.41	[3.48, 3.63]	3.60
	6	[3.36, 3.81]	3.59		
	1	[0.90, 1.17]	1.43	[10.29, 10.49]	10.24
	2	[1.87, 2.03]	1.92	[4.52, 4.63]	4.64
2nd Hour	**3**	[2.67, 2.79]	3.08	[2.89, 2.84]	2.80
	4	[1.65, 1.78]	2.02	[6.37, 6.45]	6.35
	5	[1.88, 2.12]	2.30	[4.89, 4.98]	4.88
	6	[4.73, 5.05]	7.86		

Because there were no available gap rejection data for location 6, the gap rejection model of location 5 was adopted for this location, and calibrated based on the ground-truth data.

The validation results in Table 21 and Table 22 show that some ground-truth output averages are not in the confidence level built by simulation runs. However, as discussed in the Collingwood Circle analysis, these millisecond errors can be attributed to the errors that occur when extracting the output data.

Table 22. Simulated and observed system data between 3:30 p.m. and 5:30 p.m.

	Location	Average Wait Time		Average Inter Arrival Time	
		Simulated	Observed	Simulated	Observed
1st Hour	1	[1.64, 1.77]	2.01	[3.68, 3.77]	3.79
	2	[4.62, 4.94]	5.80	[1.92, 1.95]	1.98
	3	[2.26, 2.48]	2.71	[4.50, 4.63]	4.58
	4	[4.32, 4.57]	4.44	[3.21, 3.30]	3.21
	5	[4.80, 5.29]	4.68	[2.76, 2.82]	2.81
	6	[1.23, 1.55]	1.96		
2nd Hour	1	[2.69, 2.97]	3.11	[2.85, 2.91]	2.93
	2	[8.03, 8.79]	8.43	[1.53, 1.56]	1.53
	3	[3.13, 3.64]	2.76	[4.35, 4.48]	4.41
	4	[5.05, 5.45]	4.23	[2.70, 2.77]	2.52
	5	[6.01, 6.67]	7.54	[2.51, 2.57]	2.26
	6	[3.32, 4.47]	3.86		

Table 23 shows the average network travel time for the current and alternative operational design of the Brooklawn circle. Average network travel time is the sum of travel times of all vehicles in the network during the peak period divided by the total number of vehicles. Since there is no level of service (LOS) criterion specified for traffic circles in Highway Capacity Manual, this measure can be a useful performance for comparing the efficiency of different alternatives[3].

Table 23. Comparison of average network travel times

	Morning Peak	Afternoon Peak
Current Design	[144.5-152.6]	[152.4-163.1]
Alternative 2B – Case 1	[149.4-163.3]	[175.9-193.1]
Alternative 2B – Case 2	[150.3-164.1]	[169.6-183.1]
Alternative 2B – Case 3	[153.5-162.3]	[166.7-175.3]

[3] LOS is defined for roundabouts in the Highway Capacity Manual

It is very easy to incorporate the proposed operational improvements of alternative 2B in PARAMICS. However, the timing plan of the traffic signal proposed to be deployed at the intersection of route 130 and Nansen Avenue was not available. Therefore, using the existing traffic volumes and the additional volume due to the upgrade of the Old Salem road, timing plans were obtained from SYNCHRO. Three different alternative timing plans were produced to observe the sensitivity of the results.

These results in Table 23 show that the proposed alternative leads to increased average network travel time, which is mainly due to the additional traffic signal at route 130 and Nansen Avenue / Old Salem Road intersection. Since the traffic volume on route 130 NB is high during the afternoon peak period, the effect of the additional signal is more severe during afternoon peak hours (Table 23).

Sensitivity Analysis

Unlike the substantial difference between the geometrical and operational design of Collingwood Circle, the proposed operational alternative to the Brooklawn Circle is a minor operational change. Therefore, only the sensitivity analysis of the current design of the circle was performed for this report. The signal timing of the proposed traffic signal is an unknown variable, and the effect of this variable on the average network travel time is shown in Table 23.

2^k factorial design was utilized to test the sensitivity of the simulation model to the selected variables. The efficiency of the circle is closely related to the gap rejection of vehicles at the yield signs. Locations 1 and 3 in Figure 5 were selected as the most critical locations for this purpose. Delays that occur at these locations highly affect the other locations both in morning and afternoon peak periods. It must be determined whether the model is sensitive to the mean of the exponential gap rejection probability distribution and also the target mean reaction time and headway of vehicles based on the average network travel time (response).

Table 24 and Table 25 show the levels of each input factor and the response values for the current design at morning and afternoon peak periods, respectively. 95% confidence interval with a relative error of 5% for the morning peak response value is [145.82, 150.10] seconds and for the afternoon peak is [152.3, 157.5] seconds.

Table 24. 2^4 factorial design matrix for current design a.m. period

Factor Combination	Location 1	Location 3	Reaction Time	Headway	Average Network Travel Time
1	+	+	+	+	154.0
2	+	+	-	+	151.4
3	+	-	+	+	150.5
4	+	-	-	+	1444
5	-	+	+	+	155.0
6	-	+	-	+	146.8
7	-	-	+	+	152.5
8	-	-	-	+	145.6
9	+	+	+	-	150.0
10	+	+	-	-	143.6
11	+	-	+	-	149.8
12	+	-	-	-	143.6
13	-	+	+	-	148.2
14	-	+	-	-	142.6
15	-	-	+	-	146.6
16	-	-	-	-	143.2

Table 25. 2^4 factorial design matrix for current design p.m. period

Factor Combination	Location 1	Location 3	Reaction Time	Headway	Average Network Travel Time
1	+	+	+	+	161.8
2	+	+	-	+	157.9
3	+	-	+	+	165.4
4	+	-	-	+	153.6
5	-	+	+	+	157.9
6	-	+	-	+	153.7
7	-	-	+	+	158.0
8	-	-	-	+	160.5
9	+	+	+	-	151.1
10	+	+	-	-	150.1
11	+	-	+	-	152.7
12	+	-	-	-	153.5
13	-	+	+	-	153.2
14	-	+	-	-	149.9
15	-	-	+	-	151.8
16	-	-	-	-	147.6

According to the sensitivity analysis, minor changes in the simulation model parameters (i.e. gap rejection parameters, reaction time and headway) do not drastically change the results.

CBA Results

The safety analysis for Brooklawn Circle shows that the accident rates vary considerably for Alternative 2B. The analysis also included another design alternative suggested by the DVRPC, namely Alternative 2D. However, the safety analysis results in minimal change in the estimated accident rates.

As mentioned earlier, according to the analysis conducted in the DVRPC report (4), the traffic growth rate was estimated to decline over the years because of the low projected employment rates in the surrounding municipalities.

According to the results of the base case and alternative 2B scenario presented in Table 23, the mobility is not improved overall due to the additional delay experienced at the new traffic signal. Consequently, the alternative considered by the NJDOT for Brooklawn Circle is not expected to be financially feasible based on the safety and mobility analysis.

Asbury Circle

Asbury Circle is located approximately six-miles east of the Collingwood Circle. It sits between route 35, route 66, and route 16, providing motorists access to the shore points during the summer months. Its operation design resembles an interchange rather than a circle. As seen in Figure 10, it not only provides easy access to three main routes from the local streets but also serves as an interchange between the routes.

Only the middle section of the system is a complete circle. Because there are yield-control traffic operations at each intersection, the system is analyzed as a complete circle. Six yield-controlled locations at the network are shown in Figure 10.

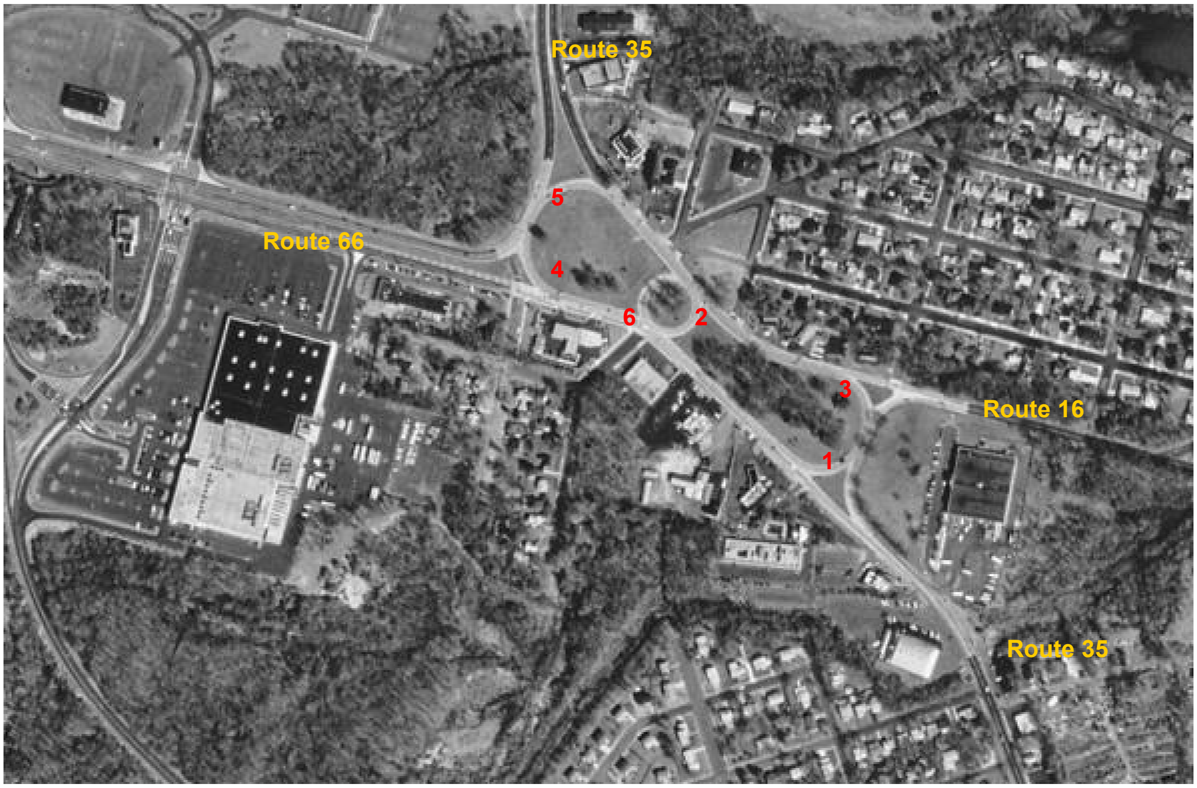

Figure 10. Aerial photograph of Asbury circle

The efficiency of this circle largely depends on the gap acceptance/rejection behavior of vehicles at these yield-controlled locations. However, four of these yield-controlled intersections play a major role in the efficiency of the circle because of the relatively heavy traffic volume traveling through. These locations are 1, 2, 4 and 5. Figure 11 through Figure 14 show the close-up aerial photographs of these locations.

In addition to its unusual geometric design Asbury circle is an unconventional traffic circle due to its traffic operation within the small circle.

In Figure 11 through Figure 14, the arrows and the solid lines represent the direction of traffic flow and the location yield signs, respectively. The roadway infrastructure in the small circle and the surrounding roadways has two-lanes without striping.

Figure 11. Aerial photograph of location 3

Figure 12. Aerial photograph of location 4

Figure 13. Aerial photograph of location 5

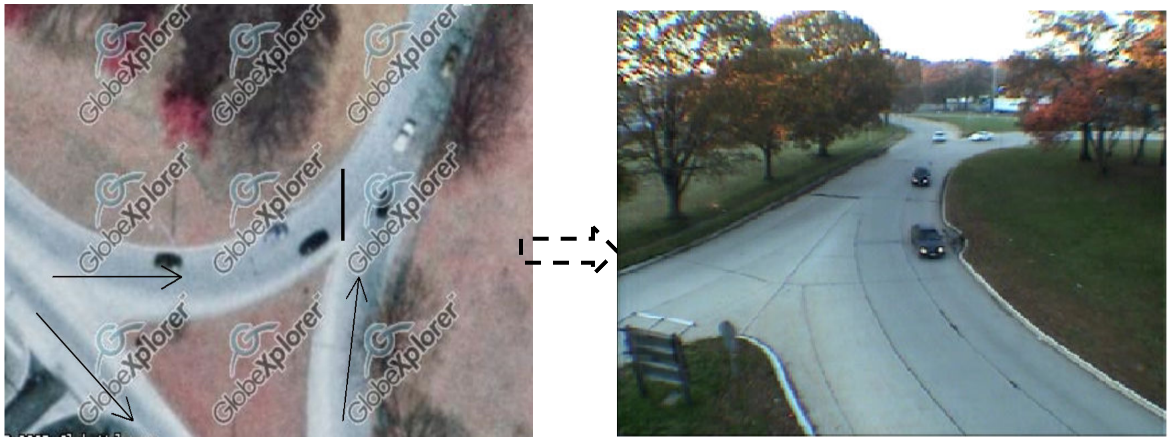

Figure 14. Aerial photographs of location 1

The traffic flow patterns during morning and afternoon peak periods are not significantly different. During the morning peak period, traffic flow is mostly concentrated on route 35 northbound, whereas during the afternoon peak period the traffic is heavier on route 66 eastbound.

Accident reports for 2000 to 2002 were provided by the Nepture and Ocean township police departments. Table 26 shows the accident history for these years. Table 27 shows the number of accidents based on severity. According to Table 26, there is a clear pattern in the accident types. Same direction, rear-end and sideswipe accident types have a high percentage of occurrence. The obvious reason to this pattern is the lack of striping and signage, and as well as high-speed levels in the circle.

Table 26. Asbury circle accident summary for 2000 to 2002

Collision Type	Count	% of Total	2002 Average
Same Direction Rear End	81	42.2 %	
Same Direction Sideswipe	62	32.3 %	16.9%
Angle	21	11.0 %	
Head On	2	1.0 %	
Fixed Object	24	12.5 %	10.4%
Other	2	1.0 %	

Table 27. Asbury circle accident summary for 2000 to 2002

Severity	Count	% of Total	2002 Average
Fatal	0	0	
Injury	48	25%	
Property Damage	144	75%	68.21%

The accident statistics in Table 27 shows the striking 25% of injury accidents. This is a coincidence of the high-speed levels and the roadway geometry. It can be seen in the aforementioned figures above that the angle of the approach directions are almost perpendicular to the yield-controlled roadway directions. The oncoming traffic is not subject to any curved roadways or rumble strips as it approaches the circle. Injury accidents are most frequent where the speed differential between the approach vehicle and the yielding vehicle is high. In other words, if a vehicle at the yield approach makes an incorrect gap acceptance the impact of the crash will be more severe.

Figure 15 shows the simulation model of the circle developed in PARAMICS software. The network consists of 148 nodes, 163 links, and 21 OD zones.

Figure 15. Asbury circle simulation model developed in PARAMICS

Model Verification

The simulation model of the circle is simulated at varying levels of traffic volumes and using different random number streams to observe whether vehicles actually behave reasonably (i.e. correct turns, accepting priority movements at junctions, proper lane changing, and using correct lanes while exiting the roadway).

Description of Data

Traffic data were collected at the circle on 31 October 2003 from 7 a.m. to 5 p.m. The POGO (Figure 4) was located at the west side of the circle with cameras directed at locations 4 and 5 (Figure 10). The portable mast with a Sony camcorder and an omni-directional camera were located at the east side of the circle with the camera directed at locations 1 and 3. Location 2 is monitored by a camcorder. The recorded traffic data were then extracted in Rutgers Intelligent Transportation Systems Laboratory. The extracted data include: (1) vehicle counts at every hour; (2) vehicle inter-arrival times at approaches; (3) vehicle wait times before yield signs at the selected locations; and (4) gap acceptance/rejection times at the selected locations.

Model Validation and Calibration Efforts

Model validation process is twofold: Subjective tests (face validation) and objective tests. The ground-truth data collected and extracted are used in objective tests. The ground-truth data involves one-day of real system data. A thorough objective test requires a set of real system data to statistically compare the simulation and ground-truth data. However, collecting and extracting the data set of a single day is a very long and costly process. Therefore, as it was postulated in the statistical analysis of the Collingwood Circle and the Brooklawn Circle, if the confidence interval of a given output variable built by the simulation data covers the observed level of the output variable, then it is assumed here that the simulation model of Asbury Circle is valid.

Modeling of Origin – Destination Matrices

The same procedure conducted for the Collingwood Circle and the Brooklawn Circle before was followed for the Asbury circle. The OD demand matrix was generated based on 12 locations by trial and error method[4].

Modeling of Inter-arrival Times

The inter-arrival of vehicles at Asbury Circle approaches is affected by the traffic signal timings near the facility. There are four traffic signals in the vicinity of Asbury circle that regulate the traffic directed to the circle. The locations of these traffic signals are circled in Figure 15.

[4] In addition to the 12 locations where the ground-truth data were collected and extracted, NJDOT provided turn counts at 4 traffic signals near the circle

The signal timing plans of these signalized intersections were provided by the NJDOT, and were coded using the actuated signals feature in PARAMICS. The inter-arrival time comparison of the ground-truth data and the simulated data is presented in the validation results section.

Modeling of Gap Rejection

The default gap rejection model of PARAMICS does not reflect realistic vehicle behavior at yield signs. At the selected locations in the network, the use of default yield control operation of PARAMICS does not yield realistic entry wait times. Without a location specific gap rejection model it is not possible to model the circle accurately, because the capacity of the circle is closely related to vehicle's gap rejection times. The API feature of PARAMICS was used to model the gap rejection behavior of vehicles at Asbury circle. Gap rejection data were extracted at the locations 1, 2, 4, and 5.

Chi-square goodness-of-fit tests were also performed for Asbury Circle to determine whether the gap rejection of vehicles follows a negative exponential probability distribution. The results are shown in Table 28 and Table 29. The use of these models in the simulation via the API feature of PARAMICS is explained in Collingwood Circle Modeling of Gap Rejection section.

Table 28. Chi-Square test of gap rejection data, a.m. period

Location	χ^2 (Observed)	$\chi^2_{k-1,0.90}$	Remark	Parameters
1	13.3	14.684	H_0 accepted	$\alpha = 1.00$, $\beta =$ 1.059
2	13.0	14.684	H_0 accepted	$\alpha_1 = 0.5$, $\beta =$ 1.279
4	4.8	14.684	H_0 accepted	$\alpha_1 = 1.50$, $\beta =$ 0.762
5	4.27	14.684	H_0 accepted	$\alpha = 2.00$, $\beta =$ 0.864

Note: α is the shift parameter and β is the sample mean of the data set.

Table 29. Chi-Square test of gap rejection data, p.m. period

Location	χ^2 (Observed)	$\chi^2_{k-1,0.90}$	Remark	Parameters
1	5.4	14.684	H_0 accepted	$\alpha = 1.75$, $\beta =$ 1.00
2	9.6	14.684	H_0 accepted	$\alpha_1 = 0.7$, $\beta =$ 1.040
4	7.53	14.684	H_0 accepted	$\alpha_1 = 1.20$, $\beta =$ 0.645
5	7.2	14.684	H_0 accepted	$\alpha = 1.75$, $\beta =$ 0.859

Note: α is the shift parameter and β is the sample mean of the data set.

The parameter values presented in Table 28 and Table 29 were calibrated to meet the actual system wait time outputs. For instance, as it is explained in the gap rejection/acceptance analysis section of the Brooklawn Circle that gap rejection/acceptance behavior of vehicles differs based on the lane they occupy. Therefore, the parameters shown in the table above was calibrated for inner and outer lanes. Data collected for the other circles show that inner lane vehicles have a lower critical gap value than the outer lane vehicles (Figure 9). Furthermore, gap acceptance of vehicles is often affected by the lane index of the approaching vehicle.

The validation and calibration analysis could be improved based on the above assumptions. As mentioned in the Microscopic Simulation Approach section, that as the study network increases, the input and output variables needed for validation and calibration analysis increase considerably. In addition to the increased effort spent on statistically validating the simulation model with higher number of variables, collecting and extracting the ground truth data is an equally important task. In the Asbury circle analysis, the study area is wider compared with the Collingwood and the Brooklawn circles. Thus, the required number of video equipment increases. Even with the video surveillance equipment described in the Description of Data section, the quality of recording did not allow for easily distinguishing the lane index of yielding and approaching vehicles during data extraction.

Results

The Asbury circle differs from the other two circles by its geometry and the capacity of its infrastructure. As in all yield-controlled traffic facilities, the efficiency of this network is related to the gap rejection/acceptance behavior of drivers and the interarrival times of vehicles on approach. It is observed in the collected ground truth data that the facility does not experience long queues or considerable delays.

Locations 1, 2, 4 and 5 are selected in validation analysis of the simulation network (Figure 10). These locations carry a high number of vehicles and have considerable impact on the overall network performance. Location 3, although carrying a high number of vehicles, has little effect on the overall system performance, and location 6 does not have heavy traffic load.

The average wait time at yield signs and the inter-arrival times are the output variables used in the validation analysis. Location 2 operates as a U-turn facility, providing access between route 66 and route 16. Table 30 displays the actual values of these variables, as well as the confidence interval obtained by the simulation model for morning and afternoon peak periods, respectively. The simulation model is simulated with independent replications until model outputs attain a confidence level of 95% with a relative error of 5% for the selected locations. Because the probability distribution of the selected output variables is not know, using the central limit theorem the sampling distributions of the population means are assumed to be almost normal with unknown variances. Student *t*-distribution is used to construct the 95% confidence interval for the population mean.

Table 30. Asbury Circle simulated and observed system outputs

	Location	Average Wait Time		Average Inter Arrival Time	
		Simulated	**Observed**	**Simulated**	**Observed**
	1	[1.91, 2.17]	2.45	[4.63, 4.87]	4.52
Morning Peak	**2**	[7.85, 8.75]	7.12	[2.57, 2.68]	2.58
(7:00-9:00)	**4**	[2.49, 2.78]	2.77	[3.0, 3.12]	3.13
	5	[1.78, 1.985]	1.98	[4.94, 5.11]	5.22
		Simulated	**Observed**	**Simulated**	**Observed**
	1	[2.29, 2.485]	2.48	[5.38, 5.60]	4.74
Afternoon Peak	**2**	[5.87, 6.27]	5.54	[2.19, 2.23]	2.36
(15:00-17:00)	**4**	[3.59, 3.82]	3.74	[2.25,2.31]	2.74
	5	[2.81, 2.96]	3.07	[3.05,3.11]	3.04

According to Table 30, some of the output ranges obtained from multiple simulation runs do not cover the observed average value of the observed system output. In the validation analysis of Collingwood Circle and Brooklawn Circle, there is always a difference between the data collection capabilities of the simulation software and the analyst.

Table 31 shows the average network travel time of the Asbury circle simulation model. Average network travel time is the sum of travel times of all vehicles in the network during the peak period divided by the total number of vehicles. Although there are no alternatives considered by NJDOT at this time for the Asbury circle, the efficiency of any future operational and safety design alternatives can be evaluated using the average network travel time as a performance measure.

Table 31. Asbury circle average network travel time results

	Average Network Travel Time (sec)
Morning Peak Period	[186.1, 188.1]
Afternoon Peak Period	[206.25, 211.01]

The developed simulation model of Asbury circle is valid based on the actual system output variable, i.e. average wait time and interarrival time. However, as performed in the model development of the other two circles, it is required to test the sensitivity of the model based on the variation of input variable values.

<u>Sensitivity Analysis</u>

Normally, if the selected simulation output is sensitive to minor changes in the input, then the model should be revised accordingly. Because there is no proposed design alternative, only the sensitivity analysis of the current design of the circle is performed for Asbury Circle.

The efficiency of the circle is related to the gap rejection of vehicles at locations 1, 2, 4 and 5. Delays that occur at these locations highly affect the other locations both during morning and afternoon peak periods. It should also be observed whether the model is sensitive to the mean of the exponential gap rejection probability distribution as shown in Table 28 and Table 29. Other important input variables are the target mean reaction time and target mean headway of vehicles. In total, there are 6 input variables that should be included in the sensitivity analysis. The effect of minor changes to these variables should be observed based on the average network travel time of the study network (response). However, in 2^k factorial method, the use of 6 input variables in the analysis requires 2^6 different scenarios to be simulated. This requires 128 different scenarios in total (morning and afternoon peak periods). Since each scenario requires at least 10 independent simulation runs to obtain statistically valid system response, the total number of simulation runs to be performed is at least 1300. Each simulation run of Asbury circle model takes approximately 8 minutes in batch mode. This corresponds to approximately 7-8 days of continuous run time. Because this required run time is highly meticulous, locations 2, 4 and 5 were included to test the sensitivity of the gap rejection model parameters, as well as the target reaction time in the analysis.

Table 32 and Table 33 show the levels of each input factor and the response values for the current design at morning and afternoon peak periods, respectively. 95% confidence interval with a relative error of 5% for the morning peak response value is [186.8 – 188.3] and for the afternoon peak is [204.1, 213.1].

Table 32. 2^4 factorial design matrix for Asbury Circle during a.m. period

Factor Combination	Location 2	Location 4	Location 5	Reaction Time	Average Network Travel Time
1	+	+	+	+	189.9
2	+	+	-	+	188.8
3	+	-	+	+	189.0
4	+	-	-	+	188.8
5	-	+	+	+	189.2
6	-	+	-	+	188.2
7	-	-	+	+	188.1
8	-	-	-	+	188.2
9	+	+	+	-	186.3
10	+	+	-	-	186.5
11	+	-	+	-	186.3
12	+	-	-	-	185.9
13	-	+	+	-	186.5
14	-	+	-	-	186.3
15	-	-	+	-	186.3
16	-	-	-	-	186.2

Note: +, and – indicate +0.3 and –0.3 changes in the mean of gap rejection distribution, and +0.2 and –0.2 sec change in the target reaction time variable

Table 33. 2^4 factorial design matrix for Asbury Circle during p.m. period

Factor Combination	Location 2	Location 4	Location 5	Reaction Time	Average Network Travel Time
1	+	+	+	+	215.9
2	+	+	-	+	216.6
3	+	-	+	+	214.2
4	+	-	-	+	215.3
5	-	+	+	+	225.0
6	-	+	-	+	214.5
7	-	-	+	+	211.1
8	-	-	-	+	217.3
9	+	+	+	-	201.7
10	+	+	-	-	200.9
11	+	-	+	-	200.4
12	+	-	-	-	200.1
13	-	+	+	-	202.5
14	-	+	-	-	201.4
15	-	-	+	-	200.2
16	-	-	-	-	200.1

Note: +, and – indicate +0.3 and –0.3 changes in the mean of gap rejection distribution, and +0.2 and –0.2 sec change in the target reaction time variable

The sensitivity analysis results show that with minor changes in the simulation model parameters do not drastically change the results.

CBA Results

The safety analysis shows that the alternative geometric and operational design is expected to reduce the accident rates by 13% based on Maycock and Hall estimation method and by 18% based on Arndt estimation method. Table 27 shows the number of injury and property damage accidents between 2000 and 2002. According to the unit accident cost estimates presented in Miller and Moffet [(8)], average accident cost of these years can be estimated approximately as $2 Million per year.

The simulation analysis of the alternative geometric design of Asbury circle showed that even with the alternative design the facility is estimated to fail in five years with a 1.5% annual traffic growth rate. The cut-off year is found out as the 4^{th} year, where the average network travel time is between [202.7, 566.5] seconds. The analysis also showed that the facility fails during the afternoon peak period faster than during the morning peak period. Finally, the projected traffic growth was applied to the base case (do-nothing scenario) and the results showed that during the afternoon peak period, the current geometric and operational design of Asbury Circle is expected to fail at 5^{th} year. Therefore, the alternative design does not improve the facility regarding the operational efficiency.

Although the simulation analysis of the current and alternative design portrays a grim description of the facility during the afternoon peak period in the following years, the analysis of future operational efficiency can be misleading due to the inability to estimate driver route choices and gap acceptance behavior under increased traffic volumes.

CONCLUSIONS

Several major difficulties are faced when using traffic simulation for project evaluation. First difficulty is understanding human behavior. The efficiency of traffic networks is largely affected by driver characteristics, as well as infrastructure characteristics. The simulation model development becomes complicated both in computer modeling of the simulation and in validation steps. Second and more important difficulty is developing a statistically valid simulation model. The analyst must remember that as the size of the network increases, the data requirements increase even more. Because collecting system data is costly and time consuming, most traffic simulation practitioners resort to calibration, which reduces the confidence in model results. A slight increase in the available system data increases the model confidence considerably [(13)].

In this report, the available off-the-shelf computerized tools that can model and analyze roundabouts and traffic circles were reviewed. The traffic circles that were analyzed in this project are not roundabouts, but traffic circles with unusual geometric and operational designs. Therefore, commonly used deterministic roundabout analysis models such as RODEL, aaSIDRA, HCS are not applicable for modeling of these traffic facilities, where the priority movements and geometric characteristics are different than those of regular roundabouts. PARAMICS is one of the few simulation software packages that can model and analyze such unconventional traffic circles. The use of a microscopic simulation tool offers various analysis capabilities. Instead of analyzing the system as a series of approaches, the system can be evaluated as a complete network. For instance, the signalized and unsignalized intersections located in the vicinity of the circle can be included in the system, and the arrival patterns of the vehicles into the circles can be modeled realistically. The impact of various changes to the operational and geometric designs can be evaluated using vehicle-by-vehicle data not only at the traffic circle, but also at the network level.

Although microscopic simulation tools offer a variety of input-output analysis options, the analyst should still assess and ensure the validity of the model input parameters. Every traffic facility has distinct characteristics whether it is a traffic circle, roundabout, intersection or freeway corridor. Extensive validation/calibration efforts might be required when the system is evaluated by using either deterministic or stochastic tools. The extent of these efforts depends on the characteristics of the facility and the scope of the analysis.

Gap acceptance/rejection behavior of vehicles in traffic circles has a dominating impact on the performance of the developed simulation models. The default gap acceptance/rejection behavior model of PARAMICS fails to simulate the study circles accurately. Extensive field data were required to represent site-specific gap acceptance/rejection behavior of drivers.

In this study, the steps of model development and validation of Collingwood, Brooklawn and Asbury traffic circles were summarized. These traffic facilities cover a relatively small area. Even for these relatively small networks, the required quantity of data was quite significant. However, to obtain a statistically valid simulation model, even more system data were required. As Law and Kelton [(6)] states “Validation is not something to be attempted after the simulation model has already been developed. Instead model development and validation should be done hand-in-hand". As more system data are obtained, the simulation model should be improved.

As mentioned in various sections of the report, as the network size increases the required surveillance resources to monitor the facility increases as well. Regarding data collection difficulties, the Collingwood Circle input variables were easier to collect and extract because of its relatively smaller size. Brooklawn Circle includes two small circles located closely. The omni directional camera could monitor the west circle with only one approach, whereas POGO could monitor the east circle and all approaches Asbury circle data collection required a careful camera set up to capture the most of the vehicular traffic. However, because the area is wider than the surveillance resources could manage, the data extraction could not include gap rejection and interarrival data based on lanes as mentioned in the Modeling of Gap Rejection section of Asbury Circle.

The results of the simulation analyses of three circles can be summarized briefly as follows.

- The proposed operational and geometric design of Collingwood Circle is not expected to adversely affect the mobility in the network. Furthermore, under increased traffic volumes the new design performs better than the current design owing to the yield-at-entry rule, which prevents lock-ups within the circle.

- The analysis of the current and proposed operational design of Brooklawn traffic circle shows that the mobility of the network does not change considerably with the new design alternative. Furthermore, the addition of the new traffic signal at the Old Salem Road and route 130 intersection is estimated to worsen the afternoon peak period queues on route 130 SB.

- Currently, the NJDOT does not have a proposed alternative design for Asbury Circle. The simulation analysis of the current design showed that the facility is expected to fail within five years during the afternoon peak periods with an assumed 1.5% increase in traffic growth rate. The new geometric design, as proposed by the RPI team, although increasing safety by 13-18%, does not prevent the failure of the system in the following years. However, the analysis of the system efficiency under projected demands can be often misleading due to various reasons as explained within the report.

In conclusion, this report presents a development and analysis of simulation models of three traffic circles in New Jersey using PARAMICS simulation software. These simulation models were validated using ground truth data collected at each circle. The novelty of the analyses presented lies in: (1) Statistically valid simulation model development and sensitivity analysis of the circles, and (2) The integration of the developed probabilistic gap rejection models at the yield controlled approaches using the API feature of PARAMICS.

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APPENDIX- THE 2^K FACTORIAL DESIGN

In many simulation studies a great deal of time and money is spent on model development and programming, but little effort is made to analyze the simulation output data appropriately. A very common mode of operation is to make a single simulation run of somewhat arbitrary length and then to treat the resulting simulation estimates as the "true" model characteristics. Since random samples from probability distributions are typically used to drive a simulation model through time, these estimates are just particular realizations of random variables that may have large variances. As a result, these estimates could, in a particular simulation run, differ greatly from the corresponding true characteristics for the model. The net effect is that there could be a significant probability of making erroneous inferences about the system under study.

Because of the importance of applying appropriate statistical analyses to the output from a simulation model of a single system, simulations of alternative system configurations should be discussed, and their results should be examined and compared. In a situation where there is less structure in the goal of the simulation study, we might want to find out which of possibly many parameters and structural assumptions have the greatest effect on a performance measure, or which set of model specifications appears to lead to optimal performance. In simulation, experimental design provides a way of deciding before the runs are made which particular configurations to simulate so that the desired designed experiments are much more efficient than a "hit-or-miss" sequence of runs in which we simply try a number of alternative configurations unsystematically to see what happens.

In experimental design terminology, the input parameters and structural assumptions composing a model are called *factors*, and the output performance measures are called *responses*. The decision as to which parameters and experimental factors depend on the goals of the study rather than on the inherent form of the model. Also, in simulation studies there are usually several different responses or performance measures of interest. Factors can be either quantitative or qualitative. Quantitative factors naturally assume numerical values, while qualitative factors typically represent structural assumptions that are not naturally quantified. Factors can also be classified as being controllable or uncontrollable, depending on whether they represent action options to managers of the corresponding real-world system. Usually we shall focus on controllable factors in simulation experiments, since they are most relevant to decisions that must be made about implementation of real-world systems. In a mathematical modeling activity such as simulation we do, after all, get to control everything, regardless of actual real-world controllability.

In the early stages of experimentation, when we do not know exactly which factors are important and how they might affect the responses, the 2^k factorial design is pretty useful. We want to get an initial estimate of how each factor affects the responses given that there are k ($k \geq 2$) factors. We might also like to determine whether the factors interact with each other, i.e., whether the effect of one factor depends on the levels (various values) of the others. An economical strategy, called a 2^k factorial design, requires that we choose just two levels for each factor and then call for simulation runs at each of the 2^k possible factor-level combinations, which are sometimes called design points. Usually a minus sign is associated with one level of a factor and a plus sign with the other; which sign is associated with which level is arbitrary, although for quantitative factors it may be less confusing if the minus sign is associated with the lower numerical value. No general prescription can be given for how one should specify the levels. The form of the experiment can be compactly represented in tabular form. The following table is an example for $k = 3$.

Table 1. Design matrix

Factor combination (Design point)	Factor 1	Factor 2	Factor 3	Response
1	–	–	–	R_1
2	+	–	–	R_2
3	–	+	–	R_3
4	+	+	–	R_4
5	–	–	+	R_5
6	+	–	+	R_6
7	–	+	+	R_7
8	+	+	+	R_8

Here the variables R_i for $i = 1, 2, \ldots, 8$ are the values of the response when running the simulation with the i^{th} combination of factor levels. For instance, R_6 is the response resulting from running the simulation with factors 1 and 3 at their respective "+" levels and factor 2 at its "–" level.

The *main effect* e_j of factor *j* is the average *change* in the response due to moving factor *j* from it "–" level to its "+" level while holding all other factors fixed. This average is taken over all combinations of the other factor levels in the design. It is important to realize that a main effect is computed extrapolate beyond this unless other conditions (no interactions, as we shall see) are satisfied.

For the 2^3 factorial design of Table 1, the main effect of factor 1 is thus

$$e_1 = [(R_2 - R_1) + (R_4 - R_3) + (R_6 - R_5) + (R_8 - R_7)] / 4.$$

Note that at design points 1 and 2, factors 2 and 3 remain fixed, as they do at design points 3 and 4, 5 and 6, as well as 7 and 8. The main effect of factor 2 is

$$e_2 = [(R_3 - R_1) + (R_4 - R_2) + (R_7 - R_5) + (R_8 - R_6)] / 4,$$

and that of factor 3 is

$$e_3 = [(R_5 - R_1) + (R_6 - R_2) + (R_7 - R_3) + (R_8 - R_4)] / 4.$$

The above expressions for the e_j's lead to an alternative way of defining main effects, as well as a simpler way of computing them. Namely, e_j is the difference between the average response when factor *j* is at its "+" level and the average response when factor *j* is at its "–" level. Thus, to compute e_j we simply apply the signs in the "Factor *j*" column to the corresponding R_i's, add them up, and divide by 2^{k-1}. (In other words, if we interpret the "+" and "–" in the design matrix as +1 and −1, respectively, we take the dot product of the "Factor *j*" column with the "Response" column and then divide by 2^{k-1}.) For example, in the 2^3 factorial design of Table 1,

$$e_1 = (-R_1 + R_2 - R_3 + R_4 - R_5 + R_6 - R_7 + R_8) / 4,$$

which is identical to the earlier expression for e_1. So the main effects measure the average change in the response due to a change in an individual factor, with this average taken over all possible combinations of the other *k*-1 factors (numbering 2^{k-1}).

Example 1. A company that sells a single product would like to decide how many items it should have in inventory for each of the next *n* months. Let *s* be the *reorder point* and *d* be the *order quantity*. It means that if the inventory level *I* at the beginning of the month is less than *s*, then *d* items will be ordered; otherwise, there will be no order. Our experimental factors are *s* and *d* and our interest is in how they affect the expected average total operating cost. The "low" and "high" levels we chose for these factors are given in Table 2.

Table 2. 2^2 factorial design matrix

Factor	–	+
s	20	60
d	10	50

The design matrix and corresponding response variables are given in Table 3, where response R_i is the average total cost per month from a single 120-month replication.

Table 3. Example design matrix

Factor combination (Design point)	s	d	Response
1	–	–	141.86
2	+	–	141.37
3	–	+	112.45
4	+	+	146.52

The main effects are

$$e_s = (-141.86 + 141.37 - 112.45 + 146.52) / 2 = 16.79$$

and

$$e_d = (-141.86 - 141.37 + 112.45 + 146.52) / 2 = -12.13.$$

Thus, the average effect of raising *s* from 20 to 60 was to increase the monthly cost by 16.79, and raising *d* from 10 to 50 decreased the monthly cost by an average of 12.13. Therefore, it appears that the smaller value of *s* and the larger value of *d* would be preferable, since lower monthly costs are desired.

Since the R_i's are random variables, the effects are also random. To find out whether the effects are "real", as opposed to being explainable by random fluctuation, we must estimate their variances. Several methods could be used; a very simple approach for simulation experiments is just to replicate the whole design *n* times and obtain *n* independent values of each effect. These can then be used to form approximate 100(1-α) percent confidence intervals for the expected effects $E(e_i)$ using the *t* distribution with *n*-1 df. If the confidence interval for a particular effect does not contain zero, we conclude that this effect is real; otherwise we have no statistical evidence that it is actually present. As usual, larger values of *n* reduce confidence-interval width, making it easier to resolve that an effect is real. We must also bear in mind that *statistical* significance of an effect does not necessarily imply that its magnitude is *practically* significant.

While factorial designs can provide valuable assistance in understanding a complicated simulation model, they do have their limitations. In order to interpret the main effects in a literal way, we must assume that the expected response can be expressed as a simple linear function of the factors, and thus in particular assume that there are no interactions. Thus, if interactions are present, we cannot just use the main effects by themselves to interpolate or extrapolate the response values for other factor levels, but should consider the nonlinear cross-product terms.