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Impact of S-Curve on Speed in a Modern Roundabout

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IMPACT OF S-CURVES ON SPEED IN A MODERN ROUNDABOUT

A Thesis Presented

by

AKSHAEEY SABHANAYAGAM

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

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Department of Civil Engineering and Environmental Engineering
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“My parents gave me education;

My teachers gave me knowledge;

My friends gave thoughts and ideas;

My partner supported my actions;

I bow my head to all who molded me.”

- Akshaey Sabhanayagam

ABSTRACT

IMPACT OF S-CURVES ON SPEED IN A MODERN ROUNDABOUT

MAY 2018

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According to the US Department of Transportation, around 20 people die on a daily basis in a signalized intersection, with most of these resulting from angle or head-on collisions. The US-DoT's Federal Highway Administration (FHWA) has identified modern roundabout intersections to be substantially safer than signalized intersections, due in part to the reduction in conflict points from 32 in a traditional signalized intersection to 8 in a modern roundabout. Despite the increased adoption of modern roundabouts across the US, there are a number of specific design elements for which the direct impact they have on operational and safety related performance of the roundabout remains unknown. To be specific, there is currently no conclusive research on the direct effects related to the introduction of a reverse curve (S-curve) on the approach to a roundabout. Moreover, what are the impacts of S-curves of varying geometries on the approach to a roundabout? This research employed a series of microsimulation-based analyses to investigate the speed related impacts related to the introduction to S-curves on the entry to a roundabout.

An existing roundabout, in Amherst, MA, USA was used as a case study for this experiment. The data at each approach of the roundabout was collected by a static camera strategically placed to attain both the pedestrian and vehicle count during peak traffic hours. The data was manually reviewed to determine the upstream and downstream vehicle counts.

The dimensions and angles of the existing roundabout were measured from Google earth and the image was extracted to AutoCAD Civil 3D. Since the objective is to check whether S-curves near an approach have a significant impact in speed, the deflection angle of the roundabout was not altered. The turning radius and angle at the approach was cross verified by measuring it on site. The existing roundabout was considered as the base model. The four approaches of the roundabout have different entry angles and radii. The revised models were drafted by strategically placing the S-curve at each approach and by steadily increasing their deflection angle and approach radius.

The base and revised models cases were initially modelled, after which the conventional linear approach was modified to an S-curve and evaluated. Field data from the locations were to and calibrate microsimulation models on AIMSUN. The resulting trajectory data was analyzed for both the base case as well as three levels of experimental S-curves (ranging from 30 to 60 degrees) on each roundabout approach (16 total). The results provide evidence to suggest that a significant reduction in speed can be realized with a minimal amount of the reverse curvature on the roundabout approach. The trajectory output files were then imported into the Surrogate Safety Assessment Model (SSAM) to determine the number and type of conflicts experienced at each approach under each scenario evaluated in AIMSUN.

Keywords

Modern roundabout approach; Vehicle Speed; Microsimulation; S-curve or Chicane.

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CHAPTER I

INTRODUCTION

Reducing traffic congestion, while enhancing traffic safety inside the roadway system has consistently presented a challenge for roadway designers. Numerous efforts by research teams across the world have been focusing on increasing the efficiency of operation of roadway structures while also making them safer to use, as this is one of the most primary goals of the traffic industry. The fact that the modern roundabout achieves this goal with significantly better results than the signalized intersection is evident in the on-going research by contemporary traffic engineers and planners. Roundabouts have been around in other countries for quite some time now, but it was only recently that U.S traffic engineers adopted this as a more convenient and advantageous roadway design. That being said, there is still insufficient literature on the effects of a changing deflection angle, entry-approach angle, gap acceptance and pedestrian safety. Further research in this area can lead to better and more innovative designs of this spectacular roadway feature.

One of the first concerns that arise with the concept of a roundabout is the potential for crashes between vehicles entering and vehicles already circulating the roundabout. Clearly and carefully placed signs and markings can sometimes do little to restrain the man entering the roundabout from proceeding without yielding to those already in the roundabout. This is most often the cause of such collisions. The critical gap in a roundabout is the closest gap that a driver feels requires yielding to a circulating vehicle, close enough to constitute a hazard. Defining this critical gap is a primary concern in the design of a roundabout (1) Through an in-depth gathering and correlation of data regarding line of sight, acceleration of entering drivers, gap acceptance and crash histories for different entry deflection angles, the safest deflection angle at the approach of a

roundabout can be determined by developing models and performing tests and simulations. Research engineers across the world have explored and hypothesized the effects that each of these have on the efficiency of directing traffic flow and preventing collisions, this data can be tremendously helpful in devising an ideal design of the roundabout.

In a 2008 California study, Xu et al.(2) stated that circulating flow rate and speed are major factors that affect both critical and follow-up headways. Follow-up headway expresses the duration of gap needed for the second car to proceed when a queue of two or more vehicles exists at the entry. Generally, follow-up headways are shorter than critical headways. At single-lane roundabouts, critical headways ranged from 4.7 to 5.3 seconds, as compared with 2.3 to 2.8 seconds for mean follow-up headways. This result is a clear indication that follow-up headways are quite shorter than critical headways, close to being half the duration. Taking this factor into consideration while designing the approach to a roundabout can achieve significantly better results, by obtaining a required regulated reduction in the speed of the vehicle approaching the roundabout, which in turn leads to fewer collisions and a safer transit.

Fitzpatrick et al. (3) found that at the roundabout on the campus of the University of Massachusetts Amherst, the critical gap was 2.2 seconds. This research also assessed the value of employing a spatial measurement of the critical gap. The critical gap in this sense was determined to be 42 feet, but it was concluded that little value could be gained from replacing traditional temporal data with spatial data. These results and conclusions served well in determining key data required for the restructured design of the roundabout at the University, while also highlighting the lack of benefit from carrying out a spatial analysis of the design.

Taking into consideration the data, results and conclusions of these and several other published works, this study aims at modeling various entry deflection angles in a roundabout and simulating the resulting impact on the traffic flow and safety of the designs, followed by an in-depth comparison of the results obtained when simulating with the existing base model, and those of the enhanced design. The effect of deflection angles on critical headways is another important aspect that can be analyzed. The existence of thoroughly researched data will aid traffic engineers in the design of new roundabouts, maximizing the benefits of the modern approach.

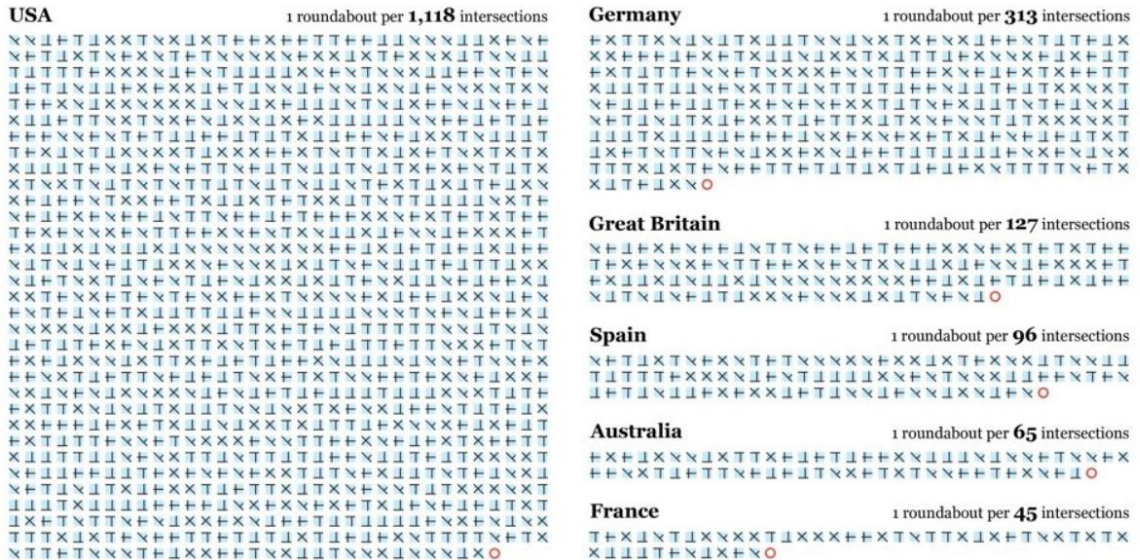
History

Modern roundabouts are more common in the UK, Australia and Europe than in America.

Roundabout : Intersection ratio

American drivers on average pass through 1,118 intersections before they encounter a roundabout. In France you are 25 times more likely to pass through a roundabout than here in America. Drivers from Australia, Spain, Great Britain and Germany also encounter roundabouts far more frequently than American drivers.

⊕ Intersection
○ Roundabout



Sources: Esri / Here, Graphic: Damien Saunder

Figure 1: Ratio of roundabouts to intersections

In the mid-20th century circular intersections came in the form of rotaries as a formidable alternative to four legged signalized intersections. This innovative substitute gained immediate popularity as it proved to achieve quicker transit and reduced the speed of vehicles without the requirement to come to a complete stop regardless of the traffic conditions and was built in several places across the globe. While these early traffic circles added aesthetic value to crowded cities, they were incredibly dangerous and impractical mainly for one reason i.e. the entering traffic had the right of way, while circulating traffic had to yield. As traffic reached a critical point, circling traffic stopped to let vehicles in, and queues in the circle blocked the upstream exits, so no one could exit the roundabout. Capacity dropped to zero as the rotaries choked and locked-up (4). The narrow entry width led to high-speed merging and over-congestion which, in turn, increased the frequency of collisions. Gradually the traffic circles had earned a negative reputation and largely fell out of favor in UK, US and in other parts of the world.

In 1966, the British redesigned the rotary and made it a much safer circular intersection. On contrast to the rotary, the vehicles entering the approach had to yield to the circulating traffic. When this was laid as an experiment the results exceeded their expectations. The yield at entry eliminated locking up, capacity increased by 10%, vehicle delay dropped by 40% and injury crashes were reduced by 40%. Britain made yield at entry universal for all roundabouts in 1966 (5). Similarly, Australia began building Yield-at-Entry roundabouts in mid-1970 (6). Subsequent evaluations found them to be extremely safe and efficient when compared to the alternative intersections. The roundabouts showed 60-75% reductions in casualty crashes after conversion (7)(8). Viewed against a background of highway fatality rates 50% higher than those of the United States (9).

Understanding the flaw of weaving theory in rotaries paved way to implement gap acceptance on a modern roundabout. Road agencies used the weaving theory to explain rotary performance. Based on J.G.Wardrop's theorem assumed that capacity of a rotary related to the length of the weaving section between an entry and the next exit: the longer the weaving section, the higher the capacity (10). As a result the central island diameter had to be too long when it had entry vehicles with high speed. When Yield-at-Entry rule had been in use for several years, Ashworth and Field observed that Wardrop's Theorem no longer adequately described the performance of roundabouts. Instead, they proposed that entry capacity was in inversely related to circulating volume (11). This central tenet is now a part of all modern roundabout capacity analysis. It is in the interpretation of this relationship that one roundabout culture now differs from another.

In 1968 FC Blackmore increased the width of entry and decreased the radius of the central island. This resulted in increasing the capacity of the circular intersection within the same space. Further experiments confirmed that the increase in approach width is directly proportional to increase in capacity (12).

America built its first roundabout in 1990, and in early 1997, about twenty-five roundabouts were in operation in California, Colorado, Florida, Nevada, Maryland, Michigan, South Carolina, Texas, and Vermont. Between then and 2009, more than 1,000 additional ones were built around the nation. Whereas, In 1993 France built its 10,000th roundabout and five years later increased the total to 20,000 roundabouts. A decade later, France completed its 30,000th roundabout. This was a significant improvement in the driving conditions in the U.S., as people began to realize the

advantages and impacts of the roundabout and its benefits over the dreaded traffic circle, which had made people quite uncertain about this kind of roadway design system.

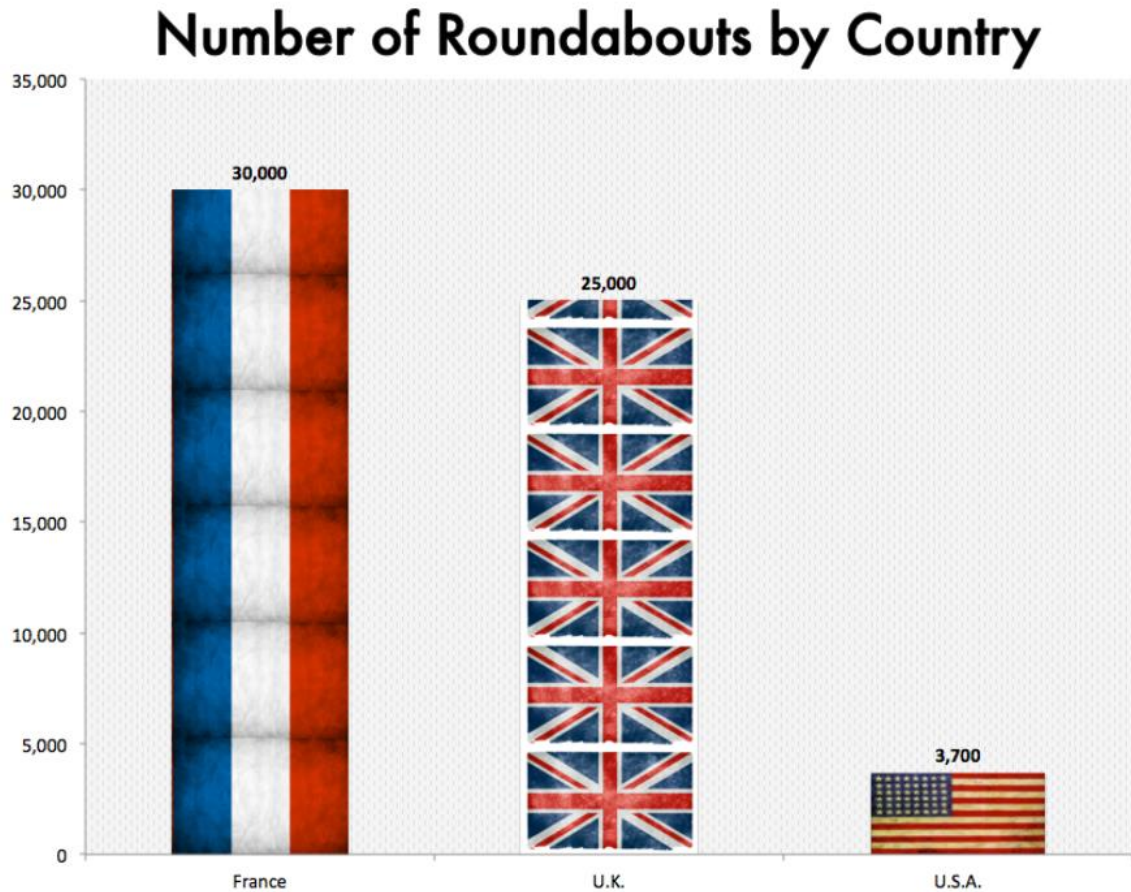


Figure 2: Number of roundabouts by country

The modern roundabout has rapidly gained acceptance in recent years across the U.S., based largely in part to the improved safety. At roundabouts the number of conflict points is reduced to eight (for four-leg intersections), as compared to 32 for a traditional intersection. In addition, unlike at conventional intersections, there are no crossing conflicts at roundabouts. Rather, all conflict points at a roundabout are classified as merging or diverging, and when collisions occur at

these types of conflict points, they tend to be less severe than those associated with crossing conflicts.

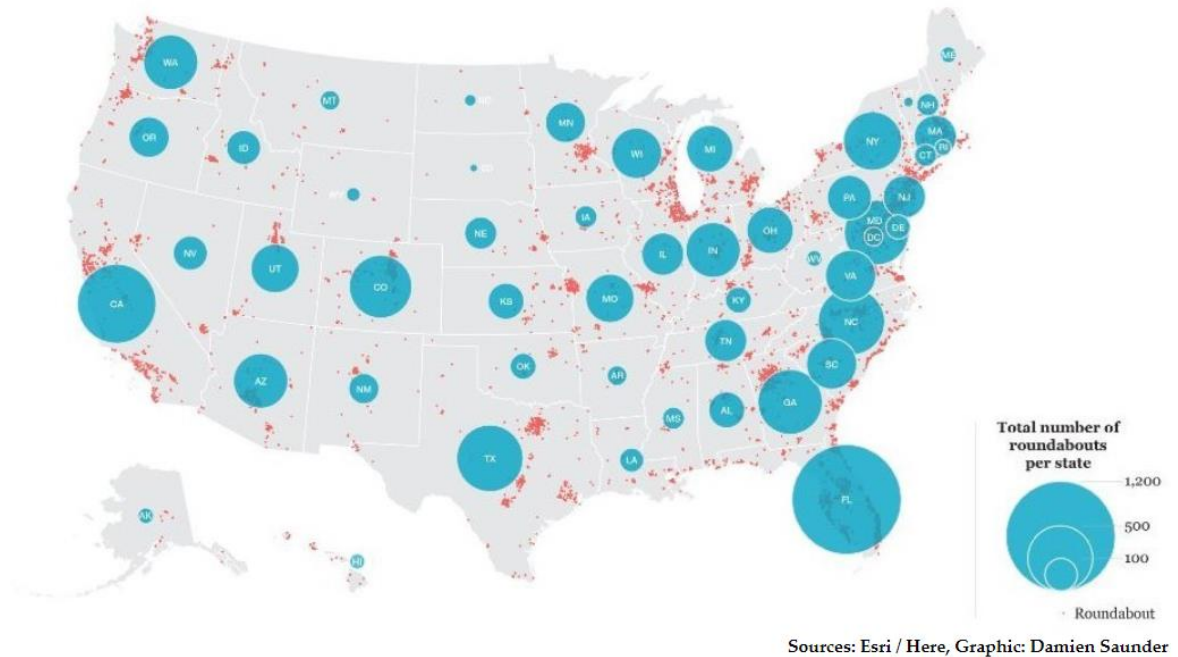


Figure 3: Number of roundabouts per state in the U.S.

In the U.S. the roundabout situation is also complicated by the interest of architects and planners. They increasingly propose to use roundabouts as the centerpieces of pedestrian-oriented new development and redevelopment of older neighborhoods, business corridors, and urban centers. Such locations typically have both high vehicular and pedestrian volumes, and their interactions at roundabouts require careful consideration. In the U.S., unlike Europeans, the drivers and pedestrians are yet to get accustomed to the operating characteristics of a roundabout. Consequently, the effectiveness of roundabouts cannot be promoted solely on the basis of demonstrated safety improvements for vehicular traffic. Land planners and transportation professionals are eager to learn more about pedestrian safety at roundabouts.

Costs and Economic Impact Roundabouts also cost significantly less than conventional intersections. Conventional traffic light intersections require an average of \$125,000 of equipment (“A Guide”). Also, the electricity costs \$8,000 to \$10,000 per stop light each year (“A Guide”). Findings also show that roundabouts improve the surrounding commercial venues. In 1999 Golden, Colorado changed four intersections into roundabouts. They created a commercial roundabout district. This district had experienced a decrease in injury crashes by 94 percent, and a decrease in overall crashes by 88 percent. Also, the commercial district experienced a sales tax revenue increase of sixty percent which resulted because of the traffic volumes that increased by 35 percent (more customers), speeds that decreased by 30 percent (more time to be allured by signs of stores), and increased traffic volumes of 35 percent (Sides 2). Roundabouts not only cost less to maintain than typical intersections, but also have the capability to improve the appeal of an area. Roundabouts often refresh the image of a community; after all, the new roundabout consists of new pavement and signs. The fresh image allures people to the area. More people yield more customers.

(13)

An important effect of the approach angle of the roundabout is the inevitable reduction in speed of the vehicle as it approaches. The driver is required to slow down in order to maneuver the curved path, a substantially reduced speed when compared to a signalized intersection. This reduction in speed increases the safety factor of the roundabout. Since energy dissipated in a collision is proportional to the square of the speed difference between two objects, lowering speeds makes surviving a crash much more likely. The most common approach to achieving the reduced speeds is through vehicle path deflection. More specifically, many traffic engineers already use splitter islands, tapers, advanced warning signage including reduced speed advisories; “shark’s

teeth” yield pavement markings, and chevrons mounted on the center island to warn drivers of the geometric change and the responsibility to yield to circulating traffic. However, sometimes these countermeasures alone prove to be insufficient to achieve the reduced speeds desired. By physically forcing drivers to navigate through a specific angle of deflection, roundabout designers can control the operating speed of a roundabout. Sharper angles of deflection at entry are hypothesized to result in lower speeds than shallower approach deflections. That being said, designing a very sharp approach angle could prove to reduce the speed of the vehicle quite drastically and bring about undesirable effects like impeding traffic leading to a larger transit time or failure to reduce speed which could cause the driver to lose control and not keep to the lane or even collide with another vehicle. Careful research and experimentation is required to provide an accurate and ideal deflection angle to the approach.

Literature Review

In Colorado, Ariniello (14) analyzed the comparison between roundabout and signalized intersection in Colorado shows that there is a reduction in the total travel time of vehicles. Several specific design strategies, ranging from traffic control devices to physical design alterations have been employed to help manage speed at roundabouts. Many of these treatments have been covered in the literature and are reviewed in the following section.

Among the most common countermeasures employed at roundabouts are signage and pavement markings. A 2011 study by Montella (15) in Italy analyzed the crash history of 15 roundabouts from 2003 to 2008, while also taking an annual inventory of field conditions. The researcher found that missing or faded yield lines contributed to 68 crashes. Furthermore, this

research also revealed that absent, faded, or poorly located yield signs were major factors in 50 crashes during the same time period.

The major benefit of roundabouts is the requirement of the driver to reduce his speed as he approaches the roundabout, something that is not required or commonly seen at conventional intersections. The achievement of this efficient design is through the scientific research and analyses of different approach angles, and the strategic design of the same. Drivers are required to slow down in order to avoid the curb on the right and the splitter island on the left to stay in the lane. The curvature of the deflection angle is a key factor in bringing about the requirement for reduction of speed. A well designed approach angle can achieve a regulated reduction in speed without impeding traffic, while one that has a lower curvature might not achieve the required speed reduction still leading to crashes, or a very large deflection angle can cause too much reduction in speed, thereby impeding traffic. The presence of this deflection angle and the subsequent maneuvering that is required to traverse it serves to prevent a significant amount of crashes, and make the ones that do occur less severe from Baranowski (16) provides an illustration of deflection at the entrance to a roundabout. Image.



Figure 4: Deflection angle in a roundabout

According to Ritchie (17), there are three key geometric features present at modern roundabouts: yield at entry, deflection, and entry flare. Yield at entry is a noteworthy evolution in the roundabout, the effects and advantages of which have already been discussed and is still one of the main reasons why several countries have readily adopted the roundabouts as part of their roadway systems. Deflection angle at the approach of the roundabout is another factor that has been shown to improve the safety of the roundabout, albeit further research is necessary to thoroughly detail the exact design and benefits. Entry flare is used on high capacity roundabouts to achieve the required speed reduction and avoiding the possibility of queueing up of vehicles.

A study by Robinson et al (18) showed that roadway curvature influenced approach speed at roundabout entrances and entry angle after capacity. He hypothesized that the transition from wide to narrow roads in the roundabout would achieve some reduction in speed as well. The primary parameter that was analyzed as an independent variable in this paper was the deflection angle. This was also referred to as “angle of entry.” The National Cooperative Highway Research Program Report 572 (19) included entry width, angle between legs, splitter island width, and intersection sight distance in their geometric analyses, but did not study angle of entry. The Maryland Department of Transportation published Roundabout Design Guidelines (20), in which deflection is defined as the physical slowing of vehicles through the roundabout achieved by causing the driver to curve around the central island. Deflection increases safety of the intersection by lowering entry and circulating speeds. This paper asserts that adequate deflection of the vehicle entering a roundabout is the most important factor in facilitating safe operation. Furthermore, circulating speeds should be restricted to less than 30 mph. The following methods are suggested to achieve appropriate deflection:

- The alignment of the entry and the shape, size, and position of approach splitter islands
- A suitably positioned and sized central island
- The provision of a staggered or non-parallel alignment between any entrance and exit.

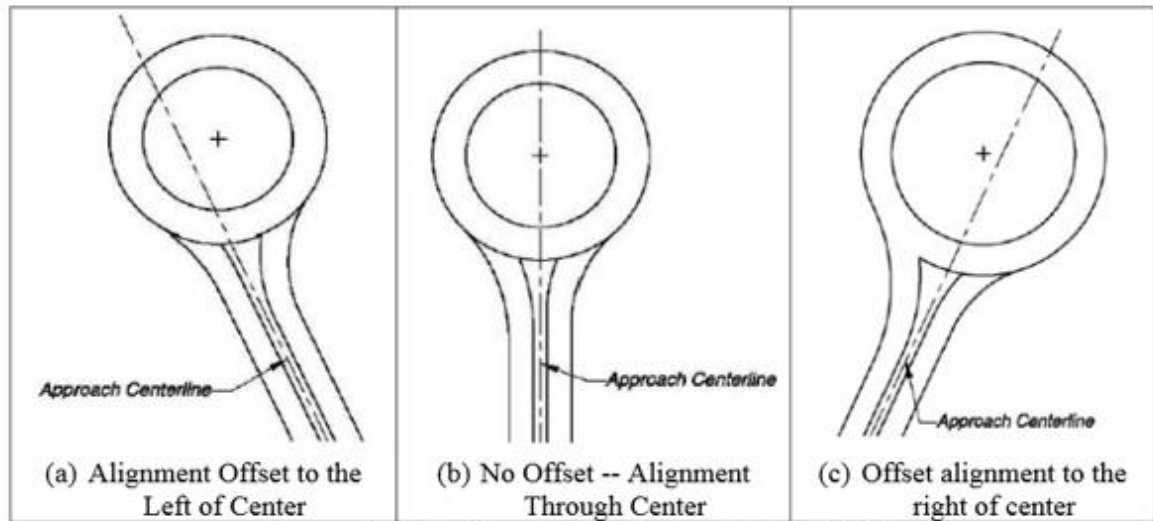
The design speed of 30 mph is achieved when a vehicle 7 feet in width has a radius of 430 feet. A sideways force of 0.2g is used to determine this value. Deflection curve radii suggested by the Maryland Department of Transportation for different design speeds are provided in Table 2.

Design Speed (mph)	Deflection Curve Radius (feet)
12	60
15	100
20	180
25	290
30	430

Table 1: Recommended Deflection Curve Radius by Design Speed

Oregon State University researchers (21) also produced a relevant paper in 2013. They analyzed roundabouts in the context of determining safety performance functions (SPFs). Entry alignment and offset was identified as a key element affecting the safety of roundabouts. They suggested that the center line of an approach leg is usually aligned with the center of the inscribed

circle at a roundabout. This corresponds to a deflection of zero. The authors state that environmental restrictions or geometric requirements may necessitate an entry offset. The extent of this deflection influences entry speed. A figure illustrating deflection designs is shown below.



Source: NCHRP Report 672 (Rodegerdts et al., 2010)

Figure 5: Roundabout Deflection Geometric Designs [11]

The National Cooperative Highway Research Program Report 672 (22) reviews the effect of entry alignment on operating speeds and safety. It also declares the importance of reducing the vehicle path radius to promote slower speeds. However, it states that consistency of speeds between entering and circulating vehicles is also desirable from a safety standpoint. Another issue raised is the need to accommodate the design vehicle. A tight radius (small deflection angle) may be problematic for truckers to negotiate. It is also necessary to consider the environment surrounding the roundabout and the speeds desired. A rural setting is less likely to experience pedestrian and bicycle volume on a regular basis than a central business district and slower speeds should be achieved in the latter case. Hence, the entry deflection must be consistent with the speeds desired.

Aty and Hosni (23) recommend an entry angle of 30 degrees. They state that a smaller angle reduces the driver's visibility to the left and a larger angle requires excessive braking. This research, though, primarily focused on capacity as a measure of effectiveness.

The increase in central angle of the vehicle path curvature was found to decrease the relative speed between entering and circulating traffic. The author of the 2000 study recommended that the entry path radius should not be much larger than circulatory radius. Zegeer et al.(6) found that deflection at the roundabout entrances should be set to control speeds between 15 and 18 mph. Russell et al (24)(25) of Kansas State University cited a 1993 Australian study by Troutbeck, in which it was stated that "Adequate deflection through roundabouts is the most important factor influencing their safe operation". The Maryland Department of Transportation published Roundabout Design Guidelines (26), in which the deflection angle causes the driver to reduce speed as the curve enters the central island. This paper asserts that adequate deflection of the vehicle entering a roundabout is the most important factor in facilitating safe operation. The Washington State Department of Transportation Roundabout Design Guidelines (27) stated that the chicanes (Fig.1) are a type of horizontal deflection which has significant impact in traffic calming and reducing the speed of the vehicles at high speed approaches.

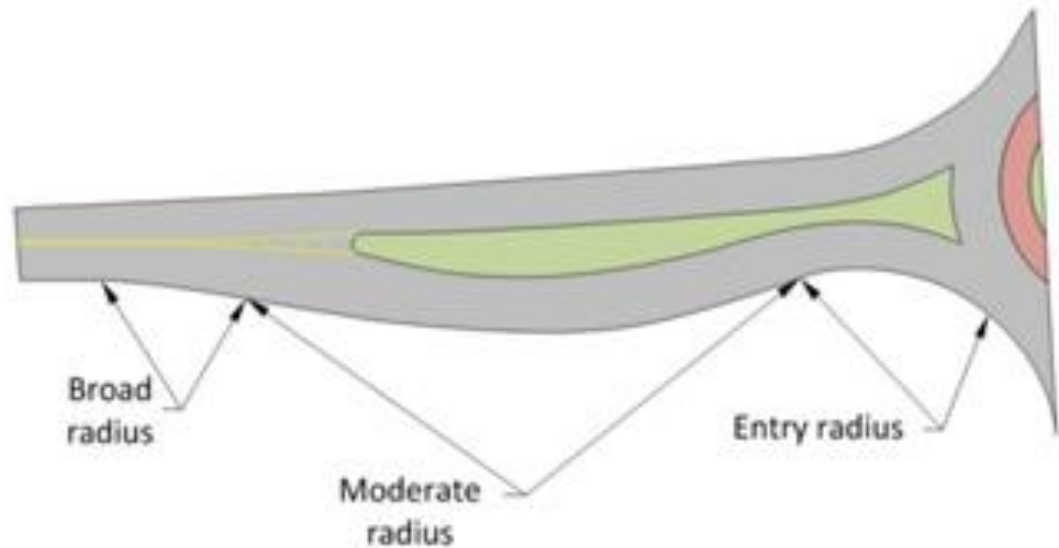


Figure 6: Chicane or S-Curve at Roundabout Approach

Isebrands (28) reports that the traffic circles are characterized by little or no deflection angle. The author states that this particular aspect encourages high speed. By comparison, the article states that at modern roundabouts, all drivers are deflected to the right, resulting in 40% reduction in total crashes and 80% reduction in fatal and injury crashes as compared to traffic calming circles. The variation in degree of deflection angle is not considered.

The goal of this study is to check if a reversed curve or S-curve approach decreases the speed of the vehicle entering the modern roundabout approach. Further, the focus of this research is to check whether the line of sight of the driver increases proportionally with the increase in central angle of the S-curve. The hypothesis of this paper is based on these two factors having a positive impact on both vehicle and pedestrian safety.

CHAPTER II

METHODOLOGY

Site Selection

The single lane modern roundabout in Amherst, MA, USA was selected as a suitable case study for experimentation. The roundabout, pictured in Figure 2 is present at the intersection of North Pleasant Street (North and South), Eastman Lane (East) and Governor's Avenue (West). Situated in the UMass campus, the roundabout undergoes periods of sudden, yet variable demand, with a mix of vehicular, pedestrian and bicycle volumes. This was a convenient location for the study, having the right usage which could be efficiently and easily monitored to acquire the data required for simulation and analysis.



Figure 7: A top view picture of the roundabout test site

Data Collection

Field data was captured at multiple time periods (both AM and PM peak) as the base input for the microsimulation models. The microsimulation model was built on AIMSUN, in part, because of the ability to manipulate geometric conditions as a function of available sight distance. The data collected consisted of vehicular traffic demand, pedestrian traffic demand and trajectories. Traffic flow was measured as the input of an OD-matrix for this project. It describes the total traffic flow entered to the roundabout from each direction.

Entrance	<i>South Bound</i>	<i>West Bound</i>	<i>North Bound</i>	<i>East Bound</i>	<i>Total</i>
Exit					
<i>South Bound</i>	0	126	158	345	629
<i>West Bound</i>	121	0	294	64	479
<i>North Bound</i>	98	78	0	72	248
<i>East Bound</i>	105	153	53	0	311
<i>Total</i>	324	357	505	481	1667

Table 2: OD Matrix for evening peak hour traffic

Road Inventory

AIMSUN software was used to model the selected roundabout. Because details about the geometric data and the speeds were required for the modelling, specific geometric dimension were obtained from a combination of design plans and field measurements. The campus roundabout was drawn in Auto-Cad Civil-3D in accordance to the existing layout and scale. Before changing the geometry of the approach, the stopping sight distance (SSD) for the roundabout was calculated from the first conflict point with the pedestrians in the roundabout. Since the main purpose of the S-curve was to reduce the speed and increase the line of sight for the drivers, the length of the SSD i.e.; 139-152 feet was taken as the length of the S-curve. There were a set of 5 experiments to figure out the optimum S-curve. The UMass roundabout was replicated into 3 trials with varying central angle in the S-curve ranging from 30, 45 and 60 degrees as shown in Figure 2.

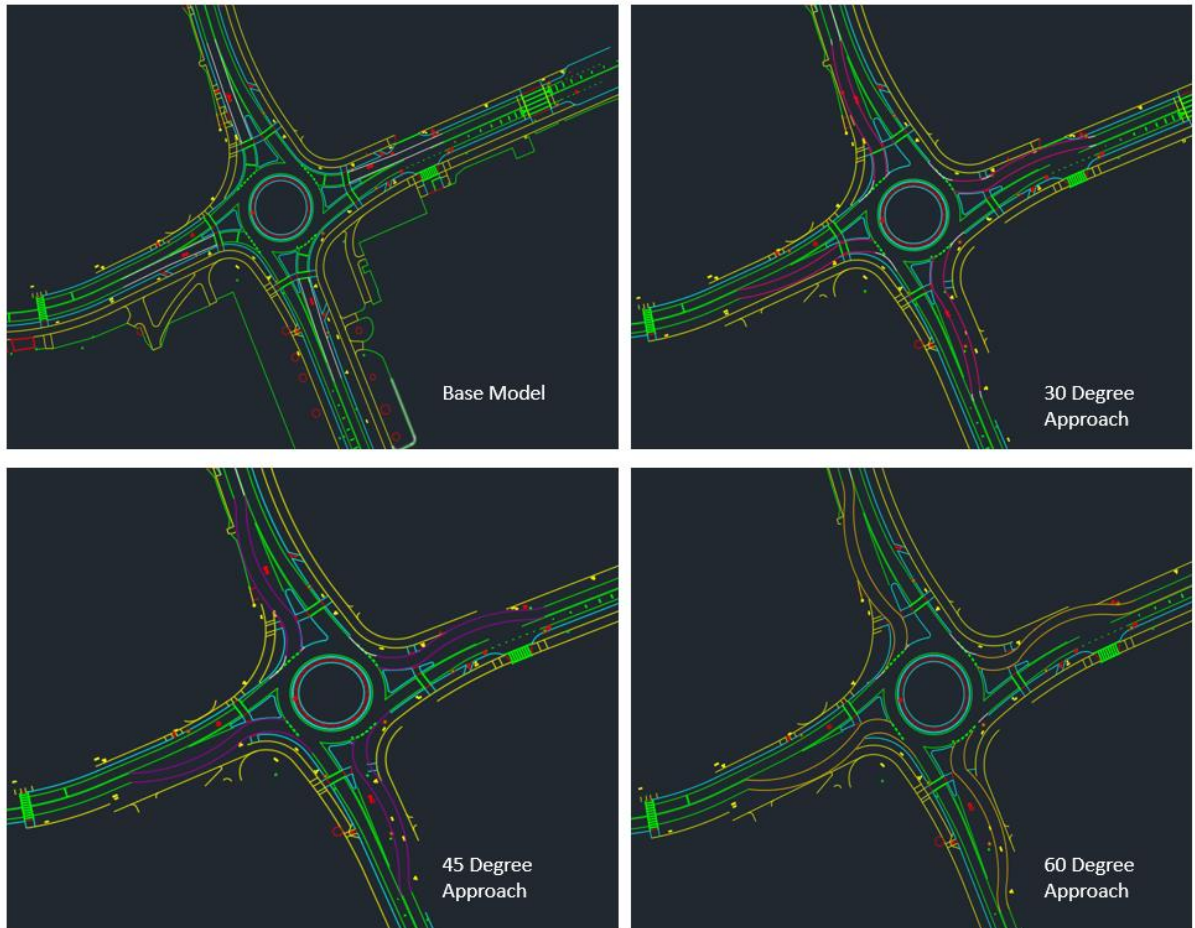


Figure 8: Aerial view of Auto-Cad figures for the Base and 3 Experimental S-Curve models

Micro-simulation

Data acquired from the video recording was utilized to create and calibrate microsimulation models using two microsimulation software. Specifically, the models were developed on AIMSUN (Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks). Of note, an attempt to model the roundabout using VISSIM was also completed, however the model was not able to account for geometric conditions that were being manipulated within the current experiment. In AIMSUN, the roundabout feature played a significant role in reducing the speed at

the modern roundabout approach. In order to perform a complete analysis, there are five major steps in the development and implementation of this Microsimulation model. The five steps are Input data, Base model and development of 3 experimental S-curve models, error check, validation and result analysis. Data that was provided as input to AIMSUN included number and width of lanes, grades, roadway segment lengths, lane types, sight distance at approach, curves, super-elevations, radii, roundabout inscribed circle diameter, circulating lane width, and entry angles. The width of the pavement is 10 feet and pavement type is selected as roundabout for the approach and centre island. The traffic volumes were assigned from the acquired evening peak hour data in the form of an OD matrix. Separate sets of vehicle parameters are used for passenger cars and heavy vehicles. The vehicle and segment speed is set constant for both the base and experimental models. The visibility to yield was calculated based on horizontal stopping sight distance for all the models. The vehicles were set to run for a duration of 2 hours and 10 replications were run on all the models.

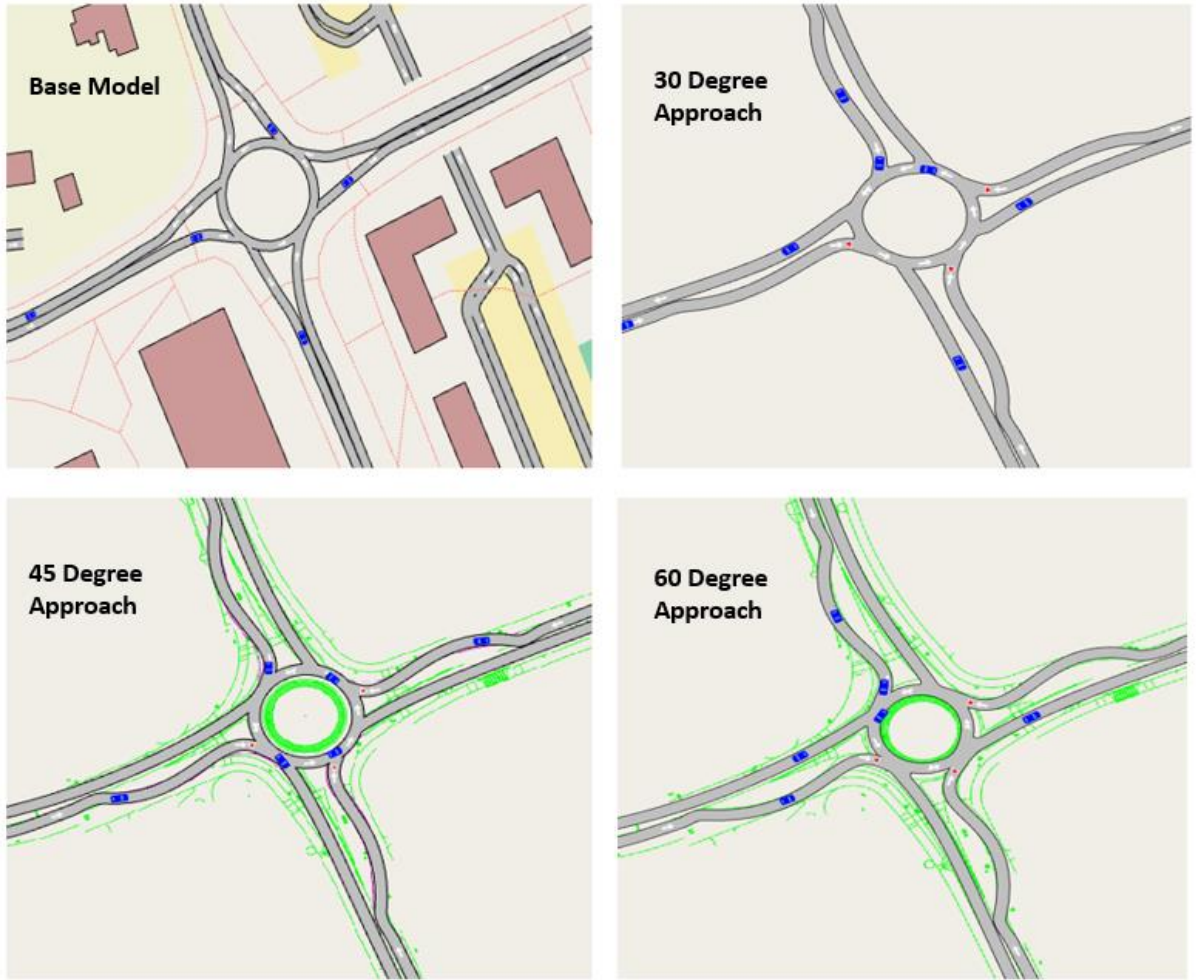


Figure 9: AIMSUN files for the Base and 3 Experimental S-Curve models

CHAPTER III

ANALYSIS AND RESULTS

Micro-simulation Analysis:

Initially, the base model and three experimental models were coded and analyzed in AIMSUN. The speed elements such as vehicle speed and section speed were constant for all the models. The radius of curvature of the approach proportionally increased with the increase in central angle of the approach. A total of 10 replication sets were set up and the results were analyzed. The speed obtained from the four models were almost the same considering the fact that the central angle was different in all the models. Most of the microsimulation software's do not consider horizontal curvature into account. As a result, no matter how steep the central angle of the approach curve is, it does not have any effect on vehicles speed.

Unlike other microsimulation software's, AIMSUN has a roundabout feature and it has significant impact on horizontal curvature but only at the approach of a roundabout. Hence the chicanes at the approaches has a remarkable effect on vehicle speeds. The increase in length of the approaches have a significant increase in the yield visibility of the approaches. A total of 10 replications were simulated. For each approach a total of 16670 vehicles were simulated and their mean speed were calculated. The results are tabulated in table 3 and plotted in Figure 10.

	<i>Base Model</i>	<i>30Degree</i>	<i>45 Degree</i>	<i>60 Degree</i>
<i>GRC</i>	27.68 mph	22.21 mph	18.94 mph	16.95 mph
<i>Eastman Lane</i>	26.94 mph	22.97 mph	17.20 mph	14.08 mph
<i>North Pleasant Street</i>	27.41 mph	21.04 mph	16.22 mph	13.25 mph
<i>Governor's Avenue</i>	27.57 mph	21.41 mph	16.54 mph	14.11 mph

Table 3: Data Collected during evening peak hour traffic

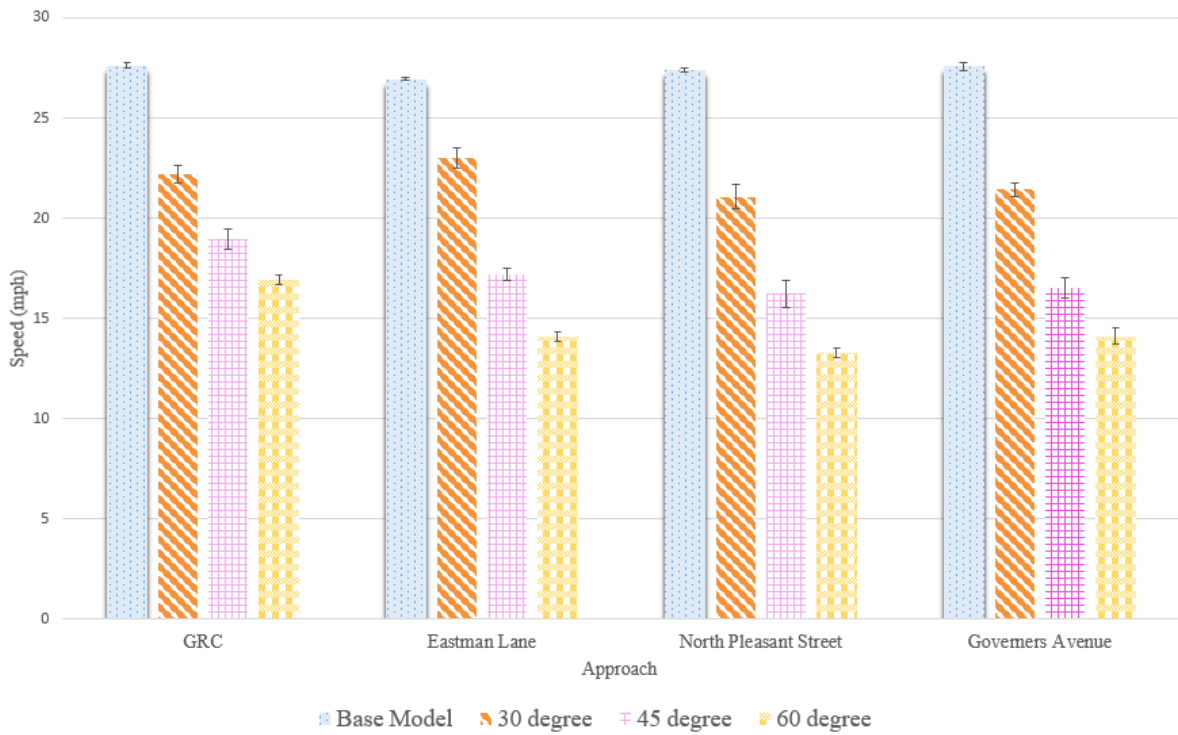


Figure 10: Mean Speed Plot for each approach for all 4 models

Trajectory Analysis

The trajectory data of each approach was later extracted from AIMSUN for all the four models. The primary reason behind trajectory based analysis was to get a clear insight on speed reduction at different parts of the S-curve approach segment. The trajectory data for 16770 vehicles was obtained at time steps of every 10 seconds. The distance of approaches for all the models ranged between 138 feet to 150 feet. The distance was split into 3 ranges to compare the vehicle trajectories between different models. Figure 5 depicts the location of the ranges at GRC approach. The first range is closest to the approach, taken as 0-75ft, the second range lies between the approach and the roundabout and is taken as 76ft-90ft, and the third range is closest to the roundabout taken as 91ft-150ft.



Figure 11: Distance Ranges marked on the Base and Experimental models on GRC approach

The trajectory data collected from AIMSUN was segregated based on the 10 replications of each vehicle that approached the roundabout, and its average speed at all 3 ranges of distance for each of the models designed. This large chunk of data had to be sorted, classified, simplified, and

analyzed. A Perl script was developed for this process of data analysis to port the raw data obtained from simulation into descriptive graphs that could indicate the results and lead to conclusions for this study. The initial data consisting of 10 replications for each vehicle was broken down and segregated to each specific vehicle, stating a vehicle ID, and its speed at each instant of distance measured as it approached the roundabout. Since there were around 1800 vehicles studied and simulated, this gave 1800x3 pieces of data to be further simplified and studied. For each of these vehicles, the data was sorted in descending order of distance from the roundabout, so the reduction in speed as the distance to the roundabout reduced was evident in the numerical values. The next step was to provide ranges of distance, instead of absolute values of distance, of the vehicle from the center island since this would serve better to analyze changing speed, instead of each vehicle being analyzed at its own absolute distance from the center island. For each vehicle, using these distance ranges created, all the values of speed that fell within each range were taken and average values of speed were computed. The resulting data had, for each vehicle, the vehicle ID and the average speed for each of the three ranges of distance chosen. This gave a clearer picture of exactly how a vehicle responded to an angular approach to the roundabout by regulating its speed. The interesting factor here was the presence of the ranges of distance, because this way the exact impact for each of the angles of curvature could be studied in comparison to each other as well as with the base model. In order to get a clear comparison, the average value of speed of all the vehicles in the study was computed for each range of distance, for each of the models. This average speed vs distance range was intended to be the main point of analysis and conclusion since it indicated the overall effect of implementing the S-Curve approach on the design of the roundabout. This final simplified data was then plotted using gnuplot to observe and compare the results. The plot contained speed on the Y-axis and ranges of distance on the X-axis. Further, the average speed of all vehicles at each range of distance was also computed, and plotted along with the curves as the

mean speed curve. This was carried out for each of the 4 models, the base model, the 30-degree model, the 45-degree model and the 60-degree model, at each of the locations at the roundabout, Eastman Lane, Governor's Avenue, GRC and North Pleasant Street. Figure 6-Figure 9 show the trajectories for all the 4 models at each location. The scatter plots represent the average speed of each vehicle over the range of distance, and the bold line represents the mean speed of all the vehicles in that range of distance. Figure 6 represents the trajectories for the 4 models at GRC, Figure 7 represents the trajectories for the 4 models at Eastman Lane, Figure 8 represents the trajectories for the 4 models at North Pleasant Street and Figure 9 represents the trajectories for the 4 models at Governor's Avenue.

SSAM Analysis

Having performed analysis on the simulation data obtained from AIMSUN, the next approach was to further use this data to identify conflict points in each design of the roundabout to identify and support the claims of increased safety of the roundabout with deflection angle over the signalized intersection. The basic idea was to use simulation models to estimate a surrogate measure for a site and to predict crashes as a function of the surrogate measure. In this investigation, the AIMSUN microsimulation model was used in conjunction with the Surrogate Safety Assessment Model. The data obtained during peak hours of traffic were used for this process, so as to receive most accurate results during the periods when the roundabout is used in the highest capacity. The obtained measurements were related to crashes using state-of-the-art modeling techniques. The idea is that the simulation models can then be used as a tool to explore the effects on safety of the roundabout with deflection angle on various operational and safety measures. The fundamental assumption, which is tested in the research, is that the outputs of the simulation models can be

related to system changes. The ultimate goal in this section of the research was to provide data that can be used to estimate crashes based on the design of the roundabout.

In this analysis, simulations were run for the whole peak hour of traffic. In order to capture the randomness in traffic, 10 simulation runs with 10 random seeds were conducted. The procedure in AIMSUN allows for selection of a random starting seed and then incrementing that by a predefined value. In this case, the starting random seed was incremented by a value of 10 for subsequent runs. AIMSUN was used to produce trajectories for each simulation run to be analyzed in SSAM for estimating conflicts. SSAM classifies conflicts into five main categories: Rear End, Lane Change, Crossing, Unclassified and Total. SSAM does not identify pedestrian conflicts separately, but according to the SSAM release notes, filtering out conflicts with speeds less than 5 mph or 7.3 ft. /sec basically represent all the pedestrian conflicts. This is because 5 mph is over the natural walking pace of pedestrians. The maximum time to collision (TTC) was set to 1.5 seconds and Maximum post-encroachment time (PET) for all the vehicles in this assessment was set to 5 seconds.

	Base Model	30 Degree	45 Degree	60 Degree
Total	79	73	158	174
Crossing	0	0	8	11
Rear-End	16	21	36	48
Crash				
Lane Change	63	52	114	115

Table 4: Number of crashes for each model

Table 4 provides details about the conflicts that were estimated in the peak hour traffic as given by the SSAM simulation. This data is a clear indication of the different types of conflict that can be expected with each deflection angle of the roundabout.

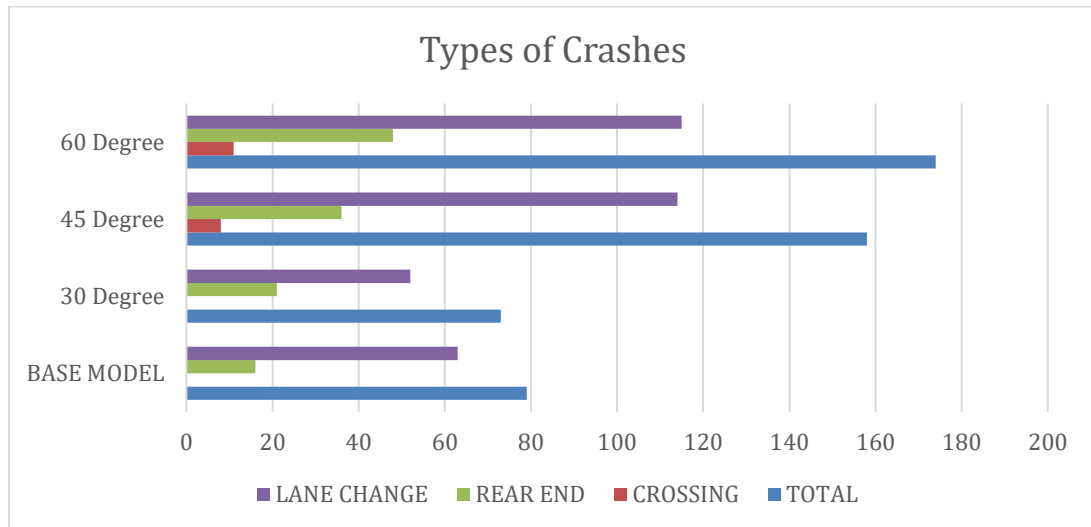


Figure 12: Types of crashes for each model

Figure 12 represents a comparison of the types of crashes that are estimated to occur between the different roundabout models under study. The graph contains details of the lane change conflicts, rear end conflicts, crossing conflicts and a total of all conflicts for each model. When comparing the results obtained between the base model and the 30 degree model, we see that the number of rear end crashes have increased and the lane change crashes have decreased in the 30 degree model. By implementing a 30 degree deflection angle at the approach of the roundabout, vehicle speeds as they approach the roundabout are required to reduce, resulting in people hitting brakes as they approach it, as opposed to if it had been a straight approach. This application of brakes in order to keep within the lanes of the roundabout could at times cause the driver to experience a rear end crash. Despite the fact that this is not ideal, the effects that are experienced

with every driver reducing speed as he approaches the roundabout because of the 30 degree deflection angle is still a far better and improved result, when compared to these possible crashes.

From the figure, we see that lane change conflicts decrease in the 30 degree model when compared to the base model. This arises from the fact that with a 30 degree approach angle, the driver has a better line of sight to view the roundabout and vehicles entering and exiting it, and has a lesser probability of facing a conflict during the lane change process. Improved line of sight was a benefit outlined at the beginning of this study, and this improvement in lane change crashes is a clear indication of this result. The 30 degree model is thus the ideal model offering the best benefits over the base model with regard to safety and efficiency of design.

CHAPTER IV

DISCUSSION

The results obtained clearly indicate that the S-Curve approach has significant impact in reducing speed at the approach of a modern roundabout. Table 5 is a quantitative representation of the impact of S-curve, since it shows a reduction in speed in the case of the experimental models i.e. the 30 degree model, 45 degree model and the 60 degree model, when compared to the base model.

	<i>30 degree</i>	<i>45 degree</i>	<i>60 degree</i>
<i>NORTH BOUND</i>	5.47 mph	8.73 mph	10.73 mph
<i>West Bound</i>	3.96 mph	9.73 mph	12.86 mph
<i>South Bound</i>	6.37 mph	11.19 mph	14.16 mph
<i>East Bound</i>	6.15 mph	11.03 mph	13.46 mph

Table 5: Speed Difference between Base and Experimental Models

Table 5 represents the difference in the mean speed that is obtained by implementing the 30 degree, 45 degree and 60 degree experimental models, as compared to the original base model (i.e., existing conditions). The following four graphs depict the reduction in speed as the vehicle approaches the roundabout for all the models.

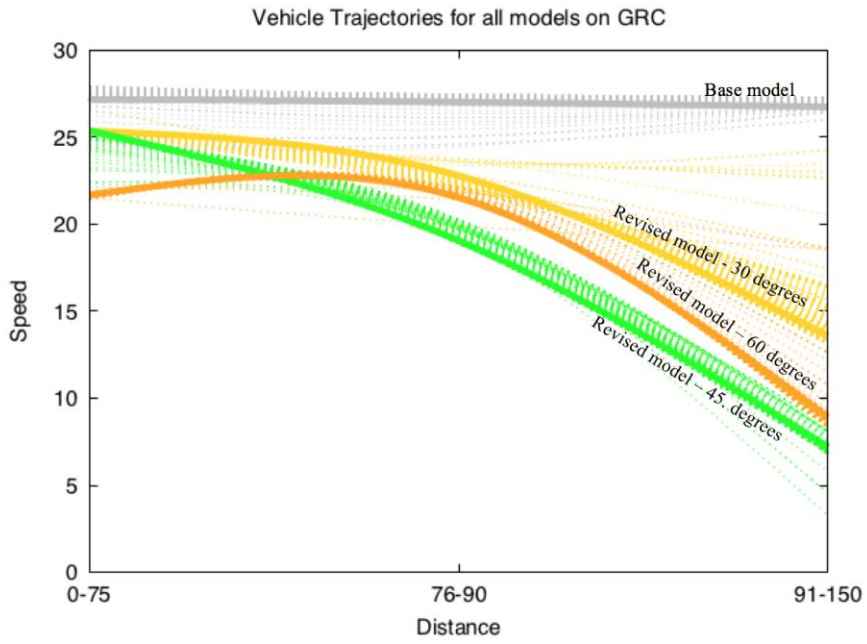


Figure 13: Individual vehicles trajectory and mean trajectory, North bound

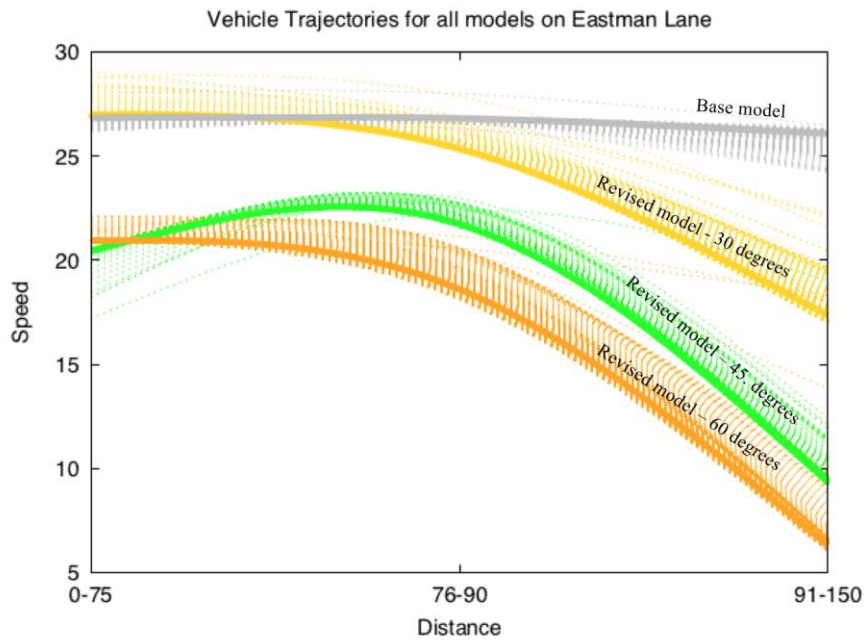


Figure 14: Individual vehicles trajectory and mean trajectory, West bound

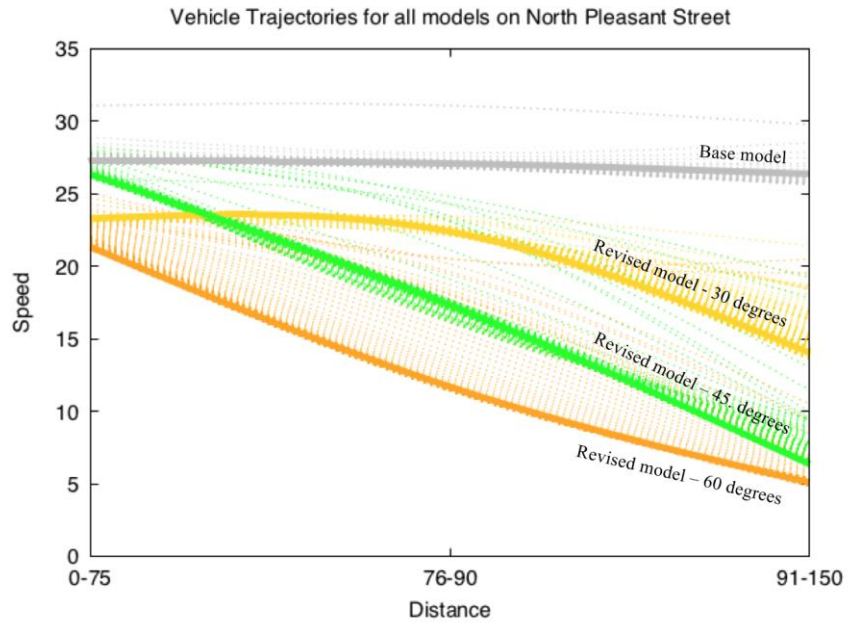


Figure 15: Individual vehicles trajectory and mean trajectory, South bound

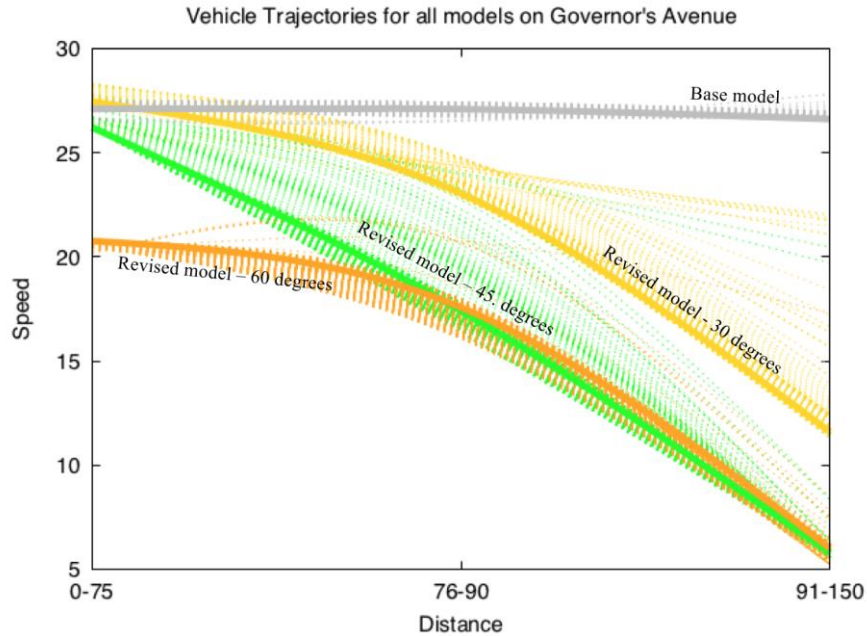


Figure 16: Individual vehicles trajectory and mean trajectory, East bound

Figure 13-Figure 16 represent the variations in speed of each vehicle measured in 3 ranges of distance as it approaches the roundabout. It is observed that for the base model i.e. the existing roundabout, the speed of the vehicle remains almost constant for the entire distance, and its speed is also greater than the speed of the vehicles in the experimental models. The vehicles approach the center island at a constant and high speed. For each of the experiments, the observed speed first increases slightly, and then reduces as it approaches closer to the roundabout. Admittedly, each roundabout approach had a different initial speed, which is a function of the upstream geometry and/or operational conditions, however, the reduction in speeds was directly related to the curvature of the S-curve. There is evidence to suggest that a significant reduction in speed can be realized with a minimal amount of the reverse curvature on the roundabout approach.

The results obtained showing both the reduction in speed benefits determined by the AIMSUN simulation and the number of conflict points determined by the SSAM simulation

suggest that the 30 degree deflection model approach to the modern roundabout would be the ideal design for the case under study. Implementing a 30 degree S-Curve approach achieves the modulated reduction in speed of the vehicle without requiring a drastic reduction in speed which would impede traffic and increase rear-end crashes as observed in the results of the 45 degree and 60 degree models, while also providing the driver a better line of sight reducing change of lane conflicts and avoiding collisions. This model brings about the two-fold improvement in transportation design systems, namely increased efficiency and safety of transit.

CHAPTER V

CONCLUSION

Summary

In conclusion, the introduction of reverse curvature on the approach to the modern roundabout produces significantly lower speeds over a greater distance than that of a traditional roundabout with a linear approach. In the existing roundabout, the speed of the vehicle as it approaches the roundabout remains relatively constant, even when it is nearing the center island. In the experimental model conditions, this speed has a direct impact in deflection angle of the approach, causing a reduction in speed of the vehicle as it approaches the center island and also increases line of sight and gap acceptance. When the driver approaches the S-curve, he/she also gets a better view of the pedestrians. This is not only a safer design for pedestrians, bicyclists, and visually impaired pedestrians, but also reduces crashes. All of these factors are directly related to the ease of use and safety of the roundabout design and the different simulations helped arrive at an ideal deflection angle that produced the best results.

The results obtained from this study detail the effects of various designs of the deflection angle at the approach of a roundabout. A qualitative and quantitative analysis of the same has been performed. The available data would be highly relevant to design engineers to attain the ideal deflection angle in the design of roundabouts when the optimum required speed of the vehicles as they approach the center island is known. The graphs depicting vehicle speed achieved with different angles of curvature and ranges of distance from the center island is an indication of this. The study also promotes the use of modern roundabouts instead of signalized intersections by stating the advantages of the former over the latter and providing evidence of the same. The

presence of well-designed modern roundabouts in a developing town increases the socio-economic value of the land bringing about a culture where people follow rules and signs owing to the smoothly flowing transit that is achieved as a result.

Future work

For future studies, the results from the different experimental models are to be further examined to determine the best model for different traffic conditions which produces optimum speed of the vehicle as it approaches the roundabout. In some instances, such extreme reductions in approach speed may not be warranted, and may lead to queueing and delays. A further analysis and simulation of pedestrian behavior and their effects on the vehicles at an S-curve is to be conducted. Specifically, a driving simulator scenario is to be created for the experimental S-curves in a roundabout using this data and tested with a minimum of 32 subjects. The final results between the microsimulation model and the driving simulator models are to be compared.

The modern roundabout is gaining popularity and further research in these areas is definitely required to provide data that helps design engineers obtain the optimum roundabout structure as it is surely a step in the right direction towards reducing traffic congestion.

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