A Report from the University of Vermont Transportation Research Center

Implementation, Driver Behavior, and Simulation: Issues Related to Roundabouts in Northern New England

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Implementation, Driver Behavior, and Simulation: Issues Related to Roundabouts in Northern New England

UVM Transportation Research Center

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1. Introduction

This chapter summarizes the work published and/or presented in the following references:

Belz, Nathan P. (2013). *Planning and Operational Models for Roundabouts.* (Doctoral dissertation), University of Vermont. Available from Library Research Annex – UVM Archives (Ref#: W15 O B419n)

Roundabouts are an emerging type of intersection design and a relatively new addition to the transportation system in the United States. This imposes two traffic engineering and research related issues. First, data and research on traffic operations and driver behavior at roundabouts are limited. Although beginning to expand in recent years, the knowledge of roundabout operations has been primarily based on data collected abroad where roundabouts are more common. Moreover, capacity and operational models are inadequate since they are derived primarily from concepts of existing stop-controlled and signalized intersections. Second, some motorists are not as accustomed to the new driving patterns associated with a roundabout. This affects traffic operations, especially at newly constructed roundabouts, but can also impact public acceptance of roundabouts which may result in part from the lack of exposure and driver confusion. This research is intended to address these issues and fill the following gaps in current knowledge for roundabouts in the United States: factors affecting public acceptance; real world roundabout operations data; and model methodology to adequately assess roundabout performance.

The research presented here can be organized into three main objectives that center on: 1) better understanding the difficulty of obtaining public approval of roundabout in the northeastern region of the United States; 2) developing a more comprehensive typology of driving behavior and actual driver maneuvers at roundabouts based on real world data; and 3) advancing the simulation modeling of roundabouts by incorporating driver behavior that is not currently represented in existing traffic simulation models. These objectives are presented in Section 2 through Section 4 of this report.

The results of this research have been disseminated in a variety of ways including refereed journal publications (1 published and 1 currently in review), two refereed conference papers in top-tier conferences (1 published and 1 in preparation), 4 professional conferences with abstract review, 1 PhD graduate degree award, and 1 research exposition.

The remainder of this report is organized around and summarizes the major findings of the primary publications resulting from this work. In Section 2, motivation and contributions of this work are presented. In Section 3, the factors that impact whether a technically feasible roundabout is accepted and implemented are discussed and the spatial and temporal variability of these implementation trends are evaluated. In Section 4, the understanding of how prevailing traffic conditions and familiarity impact driver behavior at roundabouts is improved; specifically, identifying the frequency and extent of non-compliant types of behavior that are not represented in current traffic flow theories. In Section 5, a new cellular automata (CA) model, C.A.Rsim, of traffic operations at single-lane roundabouts is introduced. The model includes a range of driving behavior identified in the work completed in Section 4 that has not been previously incorporated in traffic simulation models. Lastly, Section 6 offers some final conclusions and briefly discusses ongoing and future work.

2. Motivation and Contributions

While the technical aspects of roundabout implementation (e.g., right-of-way constraints, cost, and large vehicle accommodation) have received significant attention, the issue of roundabout acceptance is only beginning to be addressed with robust data-driven studies. This is the focus of Section 3. This research advances the understanding roundabout opposition by identifying and evaluating factors that may relate to successful implementation. More importantly, the variable development and methodology are the first such effort to quantify these types of variables using a spatial approach for both implemented and rejected roundabouts.

Current microscopic-based roundabout operational models based on gap-acceptance theory use unrealistic assumptions about the entry behavior of drivers. This is inappropriate for yield-type intersections where the lack of rigidly defined priority and traffic control creates a wider array of driver behavior than at conventional stop- and signal-controlled intersections. Not accounting for these types of behavior (presented and measured in Section 4 using field data) may affect the performance measures (e.g., capacity, delay, and queue length) generated by models currently being used in practice. Existing research acknowledges the effect of roundabout geometry on driver behavior, but does not fully document the impact of non-geometric factors. There is currently a call for research to determine whether non-geometric factors such as those studied here (i.e., driver familiarity and prevailing traffic conditions) can impact driver behavior and determine whether other non-geometric factors also need to be studied (Transportation Research Board, 2012). The research presented here seeks to: 1) provide new real-world data to characterize and document the vehicle-vehicle interactions that occur at single lane roundabout entries; 2) document the types of driver behavior that do not fit within gap-acceptance and car-following constructs; and 3) quantitatively describe how these driving behaviors vary with traffic volume and driver familiarity.

A number of real-world scenarios have been identified that affect the accuracy of current modeling techniques. NCHRP Report 672, Roundabouts – An Informational Guide (Rodegerdts, et al., 2010), identifies these as:

1. Effect of exiting vehicles. While the circulating flow directly conflicts with the entry flow, the exiting flow may also affect a driver's decision on when to enter the roundabout. This phenomenon is similar to the effect of the right-turning stream approaching from the left side of a two-way stop-controlled intersection. Until these drivers complete their exit maneuver or right turn, there may be some uncertainty in the mind of the driver at the yield or stop line about the intentions of the exiting or turning vehicle.

2. Changes in effective priority. When both the entering and conflicting flow volumes are high, limited priority (where circulating traffic adjusts its headways to allow entering vehicles to enter), priority reversal (where entering traffic forces circulating traffic to yield), and other behaviors may occur, and a simplified gap-acceptance model may not give reliable results.

Both of these scenarios, which represent limitations in existing theory, are addressed in Sections 4 and 5. The effect of exiting vehicles is referred to in this research as priority abstaining behavior where an entering vehicle abstains from maintaining priority since there is, in reality,

no conflict with the exiting vehicle. Changes in effective priority are referred to in this research as priority taking and priority surrendering. Priority taking is a situation when an entering vehicle enters when should not, causing some impedance to the follow-up circulating vehicle. Priority surrendering is when a circulating vehicle stops when they should not, giving priority to an entering vehicle. On some occasions, priority taking and priority surrendering result in priority reversal scenarios. These types of driver behavior that are not incorporated in existing theory are further discussed in Section 4.

Driver behavior is heterogeneous. The interactions between drivers are stochastic. The dimensions of any component of the transportation system are incredibly large and challenging to model. Combining these factors (e.g., vehicles, drivers, geography, environment, traffic control) together makes for a considerably complex problem. Interdisciplinary research efforts using complex systems approaches have proven to be particularly useful for modeling components of the transportation system. Transportation networks (Helbing & Nagel, 2004; Balmer, et al., 2004), phase transitions in traffic flow (Blanden, et al., 2013; Kerner & Rehborn, 1997), nonlinearity with respect to traffic congestions (Orosz, et al., 2009; Vlahogianni, et al., 2011), and self-organized routing (Yerra & Levinson, 2005; Levinson & Yerra, 2006) have been succesfully represented with complex systems methods. The stochastic and dynamic nature of driver behavior when entering a roundabout traffic stream makes a complex systems model the ideal platform for a scenario evaluation of driving behavior impacts on overall performance. Section 5 advances the understanding of how previously unaccounted for driver behavior (i.e., priority taking and priority abstaining) affects roundabout operations by using a cellular automata (CA) model. Current microscopic roundabout models that use either a gap-acceptance or car-following approach are unable to adequately account for these driver behaviors. Furthermore, current calibration and validation methods do not explicitly account for these non-compliant type behaviors. The new CA method seeks to better represent the system impact caused by non-conforming behavior typologies and the frequency of these types of behavior that occur at different traffic volume levels. The central importance of this component of the research is the advancement of current roundabout models so that the accuracy of performance measures can be improved. This ultimately impacts policy and engineering decisions on where roundabouts are implemented within the existing transportation infrastructure.

3. Roundabout Implementation in Northern New England

This chapter summarizes the work published and/or presented in the following references:

Belz, N.P., Aultman-Hall, L., Troy, A. (June 2014). *Factors Affecting Roundabout Implementation in Northern New England*, World Symposium on Transportation and Land Use Research, Delft, Netherlands. *Accepted for Presentation*

Belz, N.P., Aultman-Hall, L. (May 2011). *Roundabout Opposition and the Built Environment,* 3rd International Conference on Roundabouts, Session 5 – Getting Your Roundabout Approved, Paper #IRC3-0034, Carmel, IN.

Despite research that suggests a number of benefits when comparing roundabouts to traditional intersections (e.g., increased capacity, decreased tailpipe emissions and fuel consumption, increased safety, and noise reduction), public and political challenges to their implementation still exist in some regions of the United States. Although cost and right-of-way constraints often hinder roundabout implementation, it is also apparent that the lack of public acceptance is still a significant deterrent for some technically feasible roundabouts. Furthermore, some of the disfavor for roundabouts could in part be attributable to negative experiences with traffic circles and a prevalent inability to discern between the three circular types of intersections: traffic circles, rotaries, and roundabouts. Traffic circles, at least in New England, have been present much longer than roundabouts, which may have caused a negative stigma for all circular intersections.

Prior research has pointed to several factors driving the rejection of roundabouts as a design alternative for intersection improvement. These factors include right-of-way constraints, cost, accommodation for large or public safety vehicles and public opposition. The first three issues are technical and understood to be, for the most part, irreducible as an implementation impediment. Public opposition arises from the negative perceptions held by drivers, residents, and elected officials, and is often the principle challenge faced by a jurisdiction planning its first roundabout (Federal Highway Administration, 2000). This opposition varies by region and may be strategically addressed if a better understanding of the factors affecting opposition can be used to inform educational techniques and policy decisions.

The degree of roundabout acceptance varies regionally which is evident by implementation and conversion rates. Furthermore, there exists apparent clustering in the number of roundabouts being built when comparing states like Vermont (which currently has only seven modern roundabouts) and Indiana (which has built more than 60 roundabouts since 2001). The disparate number of roundabouts being built by different regions, states, and jurisdictions (see Figure 3.1) supports the need for a spatial analysis of factors related to implementation patterns. Previous research usually focuses solely on existing roundabouts. Locations where roundabout plans were technically feasible but were subsequently abandoned should also be studied. Moreover, they could provide insight on why there seems to be much more resistance in Maine, New Hampshire, and Vermont as compared to other states.

Five sources of Geographic Information Systems (GIS) data across Maine, New Hampshire and Vermont were brought together to examine factors affecting successful implementation: 1) roundabout and traffic circle locations (see Figure 3.2) and characteristics; 2) land cover and land

use; 3) transportation network characteristics; 4) demographics and socioeconomic variables; and 5) locations of schools and historically registered places.

The objective of this research was to explore how variables that represent proximity, exposure, built-environment, and demographics influence whether or not a technically feasible roundabout is successfully built. This research is novel in that it uses not only the known locations of existing roundabouts but also the locations of technically feasible roundabouts that were not-built and would usually not be cataloged. Prior studies have considered only built roundabout locations. Since only technically feasible roundabouts are being considered, it is assumed that public opposition would have been the primary reason for abandoning the project. Having this data allows us to directly address the issue of which factors are spatially correlated with roundabout implementation and perhaps develop a better understanding of the issues related to public acceptance of roundabouts in northern New England.
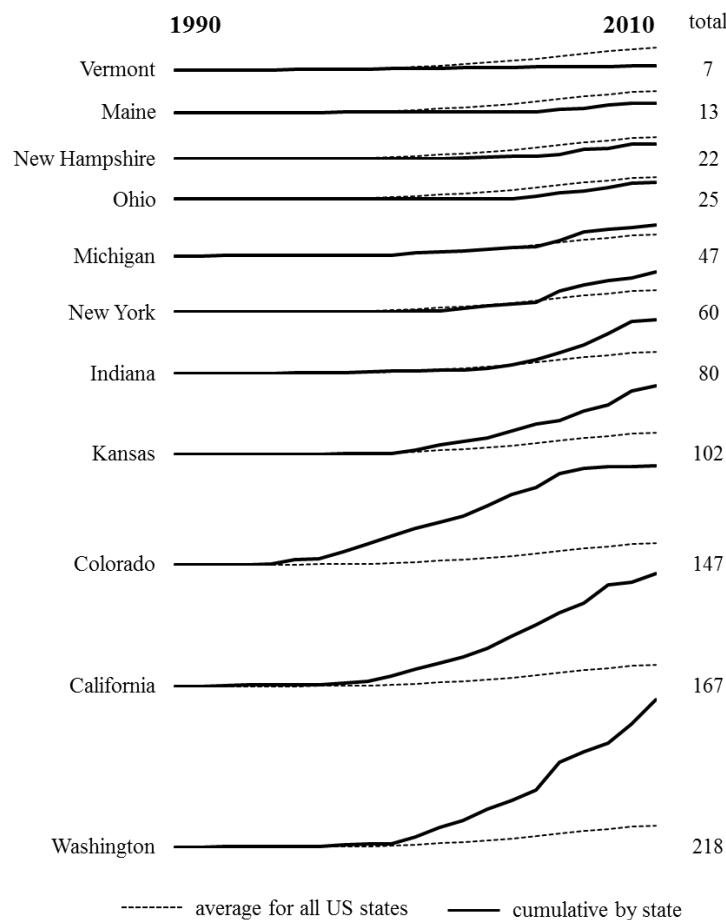
Figure 3.1. Roundabout implementation trends by year for select states
Data source: http://roundabout.kittelson.com/Roundabouts/Search

A binary logistic regression model was developed to examine the influence of spatial, temporal, physical, and social variables on successful roundabout implementation. The dependent variable of "rejected" has a value of '0' corresponding to roundabout proposals that were not-built and '1'

for roundabout proposal that were "implemented," i.e., roundabouts that were built. Before including distance to traffic circles and roundabouts variables in the model, non-linear transformations were tested to reduce a right-hand skew in the data. Roundabouts that were proposed prior to the first roundabout being built were recoded as having a value of '0' for the elapsed years variable. The model was built using a stepwise forward selection process whereby a single proximity, exposure, built environment, and demographic predictor variables are added and checked to see if all other candidate variables have had their significance reduced before moving on to the next variable. A variable is removed from the model if it is found nonsignificant.
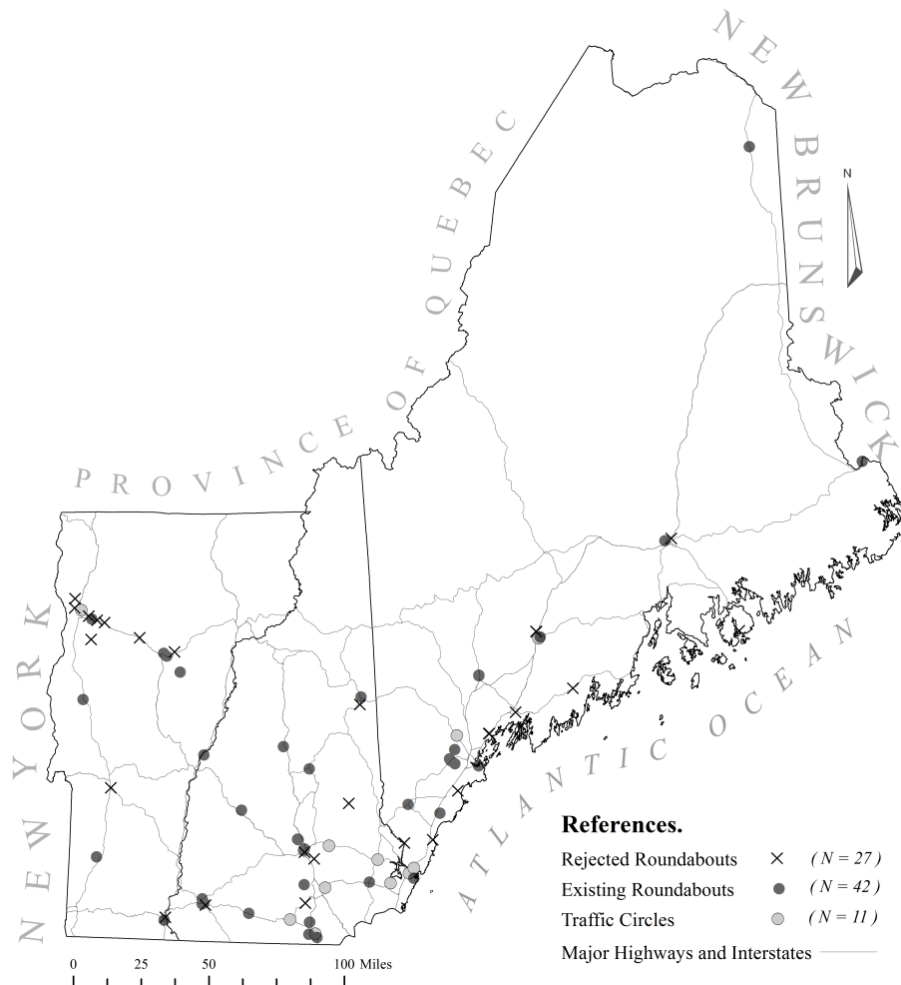
Figure 3.1. Locations of roundabouts and traffic circles in Maine, New Hampshire, and Vermont as of June 2010.

Model results (shown in Table 5) suggest that for built environment variables, higher intersection densities reduce the likelihood of a roundabout being implemented but that a roundabout is more likely to be implemented in areas with higher business densities. Intersection density is presumed

to be a measure of road pattern form (i.e., the transportation system) while business density is a measure of land use. The odds of implementing a roundabout are estimated to be about 10% less likely with an increase of 10 intersections per square mile. This suggests that other than the space and traffic constraints inherent to dense traffic networks that may make a roundabout technically infeasible, intersection density has a strong effect on roundabout implementation. Variables representing average block length were removed from the model as they were highly correlated with intersection density and presumed to also be a measure of road pattern form. The observed relationship with business density is consistent with previous work by Russell, et al. (2012) that highlights the positive impacts of roundabouts on businesses.

Table 3.1. Logistic regression estimation results.

Variable	Main Effects Model			Best-Fit Model		
	β	ρ-value	exp(β)	β	ρ-value	exp(β)
Implemented	*(reference alternative)*			*(reference alternative)*		
Built-Environment						
Intersections per sq-mi *(one-quarter mi) service area*	-0.01	0.05	1.00	**-0.01**	0.04	1.01
Businesses per sq-mi [a] *(one-half mi) service area*	**1.11**	0.02	0.33	**1.20**	0.01	0.30
Demographics [c]						
Population [a]	**-0.38**	0.04	1.19	-0.37	0.05	1.44
Age 65+ (%)	**0.16**	0.03	0.87	**0.17**	0.02	0.84
Exposure						
Year since first roundabout	-0.41	0.00	**1.51**	**-0.42**	0.00	1.51
Proximity						
Closest Roundabout [a] *(km)*	*n/a*	*n/a*	*n/a*	1.38	0.20	3.98
Constant	7.46	0.01	0.01	7.64	0.01	0.00
Observations		69			69	
Final -2 Log-Likelihood		48.00			45.09	
Null -2 Log-Likelihood		92.37			92.37	
LL Ratio (*McFadden's ρ^2*)		0.480			0.512	
Adjusted ρ^2		0.523			0.566	

Note: bold values indicate statistical significance at *p < 0.05*

[a] variable represented in hundreds

[b] variable represented in thousands

[c] Source: Summary File 3, 2000 Census of Population and Housing for Maine, New Hampshire and Vermont, prepared by the U.S. Census Bureau, retrieved July, 2011.

Demographic variables included in the final model indicate that more populated areas are less likely to have a roundabout implemented. However, areas with a higher percentage of older residents (65 years and older) are more likely to have a roundabout implemented. A 2% increase

in the number of residents over the age of 65 corresponds approximately with a 30% increase in the odds of a roundabout being implemented. The significance of the age variable counters other research contending that there is less familiarity with and less support for roundabouts amongst older populations (Retting et al., 2007; McKnight et al., 2008).

The exposure variable of elapsed years indicates that roundabout implementation becomes less likely as more time elapses. The proximity variable also suggests that being closer to an existing roundabout decreases the likelihood of a successful roundabout proposal. When comparing the log-likelihood ratio of the main effects model (with only statistically significant variables) against the full model (including the proximity variable) the chi-squared approximation with one restriction suggests that the model is improved at slightly better than a 90% confidence level. The effect size between the two models (ES < 0.05) is significant but weak. The adjusted ρ2 values are used in this case where the sample size is relatively small as to avoid artificially inflated values. Although the results of the t-tests suggested that there might be differences between the states, a nested model, which accounted for this, did not statistically improve the overall predictive capabilities of the model.

This research advances the understanding of factors related to successful roundabout implementation and contributes a new database that catalogs all built (implemented) roundabouts, non-built (rejected) roundabouts, and traffic circles through June 2010 for the states of Maine, New Hampshire, and Vermont. The results of the binary logistic regression model estimated with this new unique database of rejected and built roundabouts partially support the initial hypothesis that proximity, exposure, built-environment, and demographics play a role in the public acceptance of roundabouts. Even considering the relatively small sample size, several variables emerged as having significant association with roundabout implementation. More specifically, business density and percent of residents age 65 years and older have a positive correlation with roundabout implementation while intersection density, population, elapsed time since the first roundabout in a state, and proximity to another roundabout exhibit a negative correlation with roundabout implementation. Both the age and elapsed time since first implementation variables are counter to findings from previous studies. Possible reasoning for the age variable could be that the states included in this study (Maine, New Hampshire, and Vermont) are three of the top five states in the U.S. with the oldest median population (U.S. Census Bureau, 2000). The elapsed time variable is considered to be indicative of the implementation difficulties in Northern New England that may be different than those in other regions in which these others studies were conducted.

Findings that relate temporal exposure to roundabouts and age of residents with the likelihood of roundabout implementation are counter to what has been suggested in previous literature. This further supports the hypothesis that the challenges facing roundabout implementation in Northern New England are distinctly different from other regions in the United States and warrant further research. Although this research focused strictly on objective measures, future work will seek to better understand how subjective measures such as attitudes and values of residents about transportation and neighborhood setting influence roundabout implementation. From a policy standpoint, it is crucial to understand the key components of roundabout opposition in order to develop strategic proposal and education techniques that can help ensure their adoption in appropriate locations.

The methods employed in this research represent a new innovative approach that integrates multiple forms of data spatially to identify characteristics of areas where technically-feasible roundabouts are not being built. This includes quantifying variables that reflect spatial, temporal, physical, and community characteristics. This analysis methodology illustrates the role that spatial information plays in strategic planning for roundabout implementation. This is critically important since roundabouts can serve to increase safety and efficiency as well as decrease the environmental impacts of the transportation system. Based on these positive findings, the study scope should be broadened to states with larger spatial coverage and higher roundabout conversion rates including unbuilt roundabouts to better examine the role of proximity and exposure.

4. Typologies of Driver Behavior at Single-Lane Roundabouts

This chapter summarizes the work published and/or presented in the following references:

Belz, N.P., Aultman-Hall, L., Lee, B.H.Y., Garder, P.E. (in press). *An Event-Based Framework for Non-Compliant Driver Behavior at Single-Lane Roundabouts,* Transportation Research Record, Journal of the Transportation Research Board of the National Academies, Washington D.C.

Belz, N.P., Aultman-Hall, L. (April 2013). *That's Not How You're Supposed to Drive Through a Roundabout! Non-Compliant Behaviors at Single-Lane Roundabouts,* UVM Transportation Research Center Research Exposition, Burlington, VT.

Belz, N.P. (January 2013). *Operational and Planning Models for Single-Lane Roundabouts*, 92nd Annual Meeting of the Transportation Research Board of the National Academies, Workshop 103 – Doctoral Student Session in Transportation Operations and Traffic Control, Washington D.C.

Driver behavior at a roundabout entry is generally modeled using gap acceptance theory originally developed for stop-controlled intersections (see, e.g., Raff, 1950). This assumes that a driver enters the roundabout when there is a sufficient gap in the circulating traffic for that driver to enter safely and stops only when there is not. It has been observed that some drivers do not adhere to the yield-at-entry rule and either: 1) stop despite there being sufficient gaps or no other vehicles present; 2) enter into gaps that are neither sufficient nor safe; or 3) yield to entering vehicles while circulating. Yet, many current models of roundabout operations do not reflect these non-compliant behaviors. Because there is a lack of rigidly defined priority and traffic control at roundabouts, a wider range of driver behavior is observed than at conventional stop- and signal-controlled intersections. A common alternative to gap acceptance models are purely empirical models such as the Australian-based SIDRA model and the UK-based RODEL and ARCADY models. These also do not take into account that non-compliant behavior may differ between locations and maturity of a roundabout.

The overall research question being addressed in this study is what types of behavior do drivers exhibit when entering single-lane roundabouts? Using field data, this study focuses on a subset of driver behavior that may significantly influence roundabout performance. A new framework is developed using real world video data to describe the types of behavior observed at roundabout entries and, more importantly, to make a distinction between types of behavior that are or are not compliant with gap-acceptance theory. Also provided in this research are: new data; a new way to process video data of roundabout operations; and the implementation of a floating interval technique to measure traffic volumes in place of the more standard set interval methods.

This paper seeks to address four objectives. First, the relative frequencies of non-compliant types of driver behavior are documented. This is critical to assess if they are occurring often enough to consider in roundabout performance measures and include in a traffic simulation model. Second, the relationship between the percentage of non-compliant driver behavior and traffic volume is measured. Third, the relationship between non-compliant driver behavior and delay is analyzed to quantify the impact of these types of behavior. Finally, the level of non-compliant behavior as related to roundabout familiarity is assessed. The study area spans Maine, New Hampshire, Vermont and upstate New York; roundabout experience and implementation varies across these states. Comparing the amount of non-compliant behavior that occur at "newer" roundabouts to

the amount occurring at older roundabouts provides for a better indication of how familiarity changes behavior over time.

Based on preliminary video analysis, it was evident that the most prevalent non-compliant behavior involved a number of yield/non-yield scenarios. From observing roundabout operations and the vehicle-vehicle interactions, the behavior of entering and circulating drivers can be described as:

1) *Unhindered* – the driver does not slow down or stop because there is not a need to do so, or is unwilling to yield and chooses not to;
2) *Slow-hindered* – the driver decelerates, presumably for a perceived conflict with another vehicle, but does not come to a complete stop; and
3) *Stop-hindered* – the driver comes to a complete stop as a result of a perceived conflict that does not exist.

These definitions allow for the distinction between a "hindered" event and an "unhindered" event to be determined from video based on whether or not the brakes were applied. There are essentially three items to distinguish in data coding. Who stops (or yields) when they should not? Who does not stop (or yield) when they should and which traffic stream are they? The resulting types of behavior can then be defined as:

1) *Priority Abstaining* – An entering vehicle that stops when they should not. This occurs when a vehicle on the approach either: stops when there are no other vehicles present at the roundabout; stops when there are clearly sufficient gaps into which they could have entered; or stops for vehicles that are exiting from the circulating stream of traffic on the same leg (see Figure 4.1).

2) *Priority Taking* – An entering vehicle that goes when they should not. This occurs when a driver on a roundabout approach enters into a gap in the circulating stream of traffic that is either insufficient in size or misuses (e.g., enters late) the space of an adequately-sized gap and the circulating vehicle is impeded and must change their trajectory (i.e., apply the brakes and either slow down or stop) in order to avoid a collision (see Figure 4.2).

3) *Priority Surrendering* – A circulating vehicle that stops when they should not. This occurs when a vehicle in the circulating stream of traffic gives up their right-of-way (by either stopping or slowing down considerably) and allows entry of a vehicle that was waiting on the approach (see Figure 4.3)

Although other types of behavior were observed, priority abstaining, priority taking, and priority surrendering were clearly the most prevalent and appeared to have the greatest impact on operations. To that end, this research focuses only on the characteristics of these three non-compliant types of driver behavior.
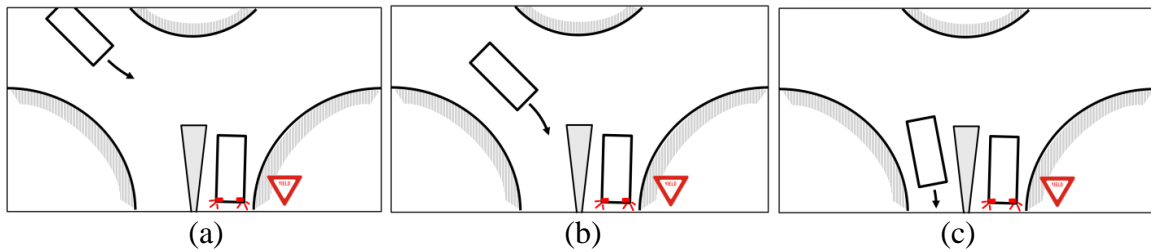
Figure 4.1. An example of priority abstaining to an exiting vehicle where an entering vehicle (a) stops at the roundabout entry upon seeing a vehicle in the circulating stream, (b) is still stopped as that vehicle begins to exit, and (c) remains stopped as the vehicle then fully exits on the same leg.
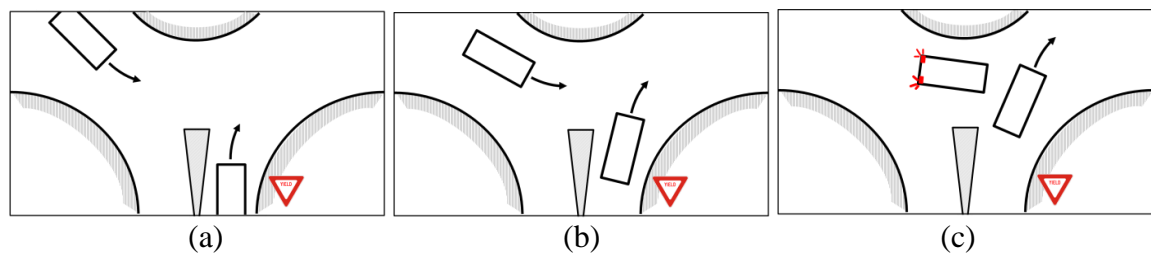
Figure 4.2. An example of priority taking from a circulating vehicle where an entering vehicle (a) approaches the roundabout entry, (b) enters into the roundabout in front of a circulating vehicle, and (c) causes that circulating vehicle to either stop or slow significantly in order to avoid collision.
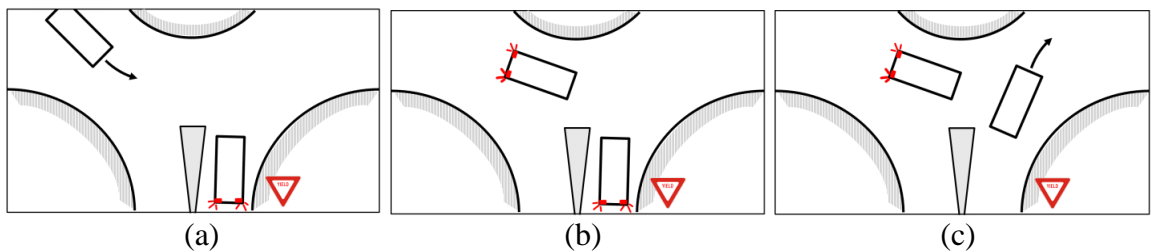
Figure 4.3. An example of priority surrendering by a circulating vehicle where (a) an entering vehicle is stopped at the roundabout entry while another vehicle is circulating, (b) the circulating vehicle stops, and (c) the approach vehicle then enters in front of the stopped vehicle in the circulating stream.

Observed priority taking and priority abstaining types of behavior as a percentage of entering vehicle volume observed for each roundabout location are shown in Figure 4.5, with priority abstaining behavior being the most prevalent. Although Glens Falls, NY was the only location that had a higher percentage of priority taking than priority abstaining, it was also the location with the highest incidence of priority surrendering. Overall, the sample size of priority surrendering observations was not large enough for statistical validity.
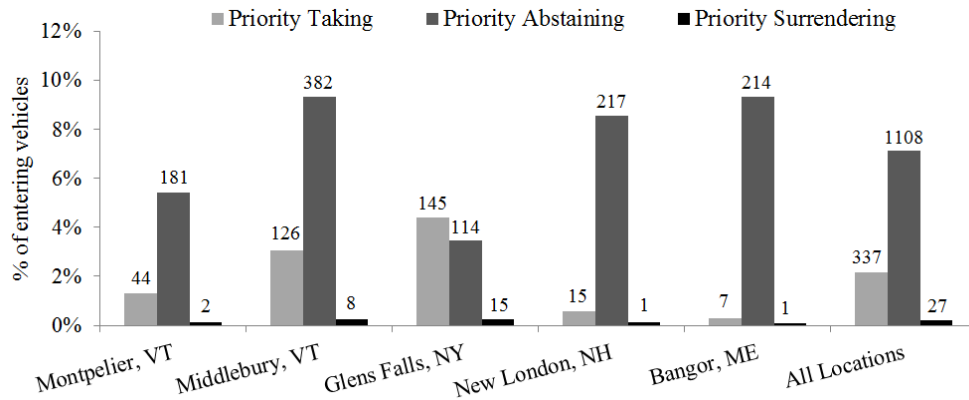
Figure 4.4. Priority taking, abstaining, and surrendering behavior by roundabout location.

Traffic volumes in vehicles per hour (vph) were determined using a twenty-second event-based volume rather than using the typical one-minute intervals used for many traffic engineering analyses. A method was needed that allows for a better representation of the gap opportunities and conflicts presented to the entering driver as they are making the decision of whether or not to enter. In general, there is a need to use a time interval that is short enough to represent uniform conditions (Hurdle, Merlo, & Robertson, 1997) yet long enough to minimize noise (Banks, 1999; Smith & Ulmer, 2003). Since the analysis is primarily concerned with yield and non-yield events, it is logical to capture volume conditions directly tied to those interactions. Rather than using set time intervals, the analysis makes use of a floating time interval centered on the arrival time of the entering vehicle, which represents the conditions experienced by each vehicle of concern.
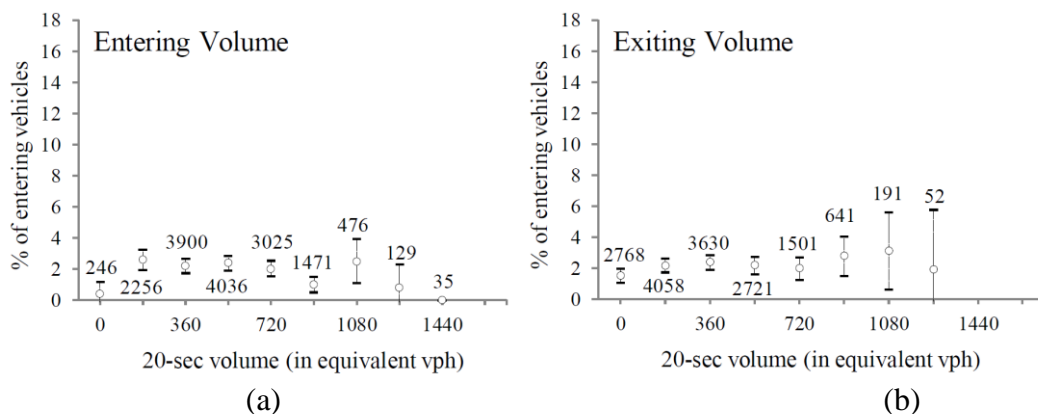
The percentage of entering vehicles that exhibited priority taking behavior was compared against a number of volume conditions for all five roundabouts (see Figure 6). Priority taking behavior exhibits a relationship with circulating volume (Figure 6c). Analysis of variance (ANOVA) was used to compare the frequency of entry vehicle behavior for different traffic volume levels. The ANOVA results showed that the effect of circulating volume was significant, $F(9, 15563) = 40.2, p < 0.001$. As circulating volume increases (i.e., the number of *potential conflicts* to which an approaching vehicle is exposed), the likelihood that an entering vehicle will take priority becomes greater. When no traffic is present, there is no opportunity to force into a gap. As the volume in the circulating stream begins to increase (when volumes are low and gaps are relatively large), there is still the opportunity for an entering vehicle to misuse a gap. As circulating traffic volume reaches 1400 vph, the percentage of priority taking may surpass 10%. The potential for a non-linear increase in priority taking behavior may represent the incremental addition of aggressive-type behavior invoked by the waiting phenomenon at higher saturation levels *(27)*. Note that the circulating and entering volume combination (Figure 6d) only displays a trend because of the strong relationship with circulating volume.

Similarly, the percentage of entering vehicles that exhibited priority abstaining behavior was compared against a number of volume conditions (see Figure 7). Priority abstaining behavior shows a significant relationship with exiting volume (Figure 7b). The ANOVA results showed

that the effect of circulating volume was significant, *F(8, 15563) = 30.1, p < 0.001*. As exiting volume increases (i.e., the number of *perceived conflicts* to which an approaching vehicle is exposed) there is a greater likelihood that an entering vehicle will abstain from maintaining priority. At an exiting volume above 1200 vph, the amount of priority abstaining may begin to decrease. This potential decrease may result from a portion of entering drivers who would have otherwise been predisposed to priority abstain who then do not since they expect that the next driver (with whom there would have been a "priority" conflict) is also going to exit once the roundabout starts experiencing sustained exiting flows. However, it should be noted that the variance in the observed values in this traffic flow range were also much higher and can be seen in the confidence intervals shown in Figure 7b.

Priority abstaining for exiting vehicles accounts for 59% *(n = 653)* of all priority abstaining behavior and occurs more often than "stopping for no reason" *(n = 145)*. Average stopped delay is also higher for abstaining behavior involving exiting vehicles than no vehicles, 3.3 seconds as compared to 2.9 seconds respectively. There was an average of 9.1 seconds of delay for priority abstaining that involved three or more exiting vehicles *(n = 63)*, essentially vehicles who are sitting at the roundabout entry and waiting as numerous vehicles exit when they could have entered. In addition, the fact that 20% of priority abstaining behavior occurred after another driver had abstained priority suggests the possible formation of informal traffic rules at roundabouts given the lack of driver familiarity. This is consistent with other research suggesting that driver behavior is influenced by the behavior of other drivers around them *(33, 34)* and that there is a tendency of drivers in such situations to ignore formal traffic rules and regulations *(35)*.

Past research suggested that relatively new roundabouts (less than five years old) may still cause confusion amongst users about correct roundabout negotiation *(24)*. Table 2 shows the chi-squared analysis results comparing priority taking and priority abstaining events occurring at newer roundabouts (in place for less than five years) with older roundabouts (in place for five years or more). There is a statistically significant decrease in priority abstaining behavior over time when comparing newer roundabouts with older roundabouts. This reinforces the idea that drivers are not necessarily becoming more aggressive over time, but rather that the number of drivers who stop when they should not (a better indication of familiarity) diminishes over time.

Figure 4.5. Means plots of observed priority taking behavior as a percentage of entering vehicles with number of observations.
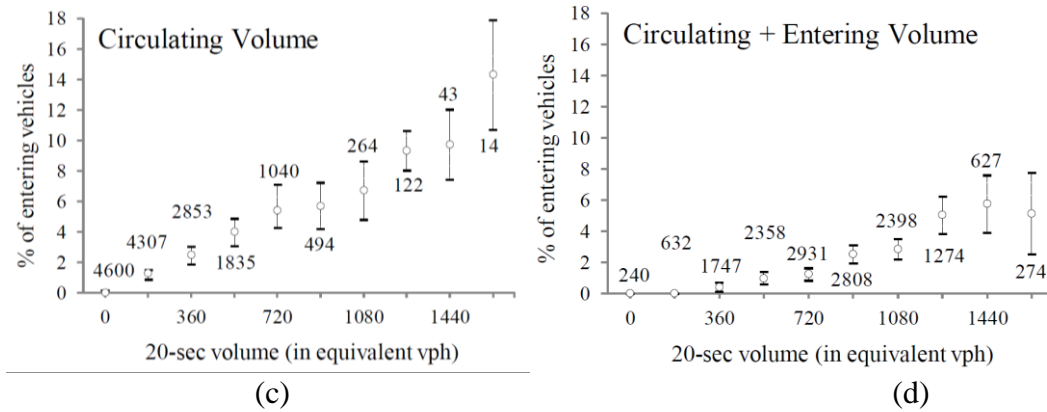
Figure 4.5 (cont.). Means plots of observed priority taking behavior as a percentage of entering vehicles with number of observations.
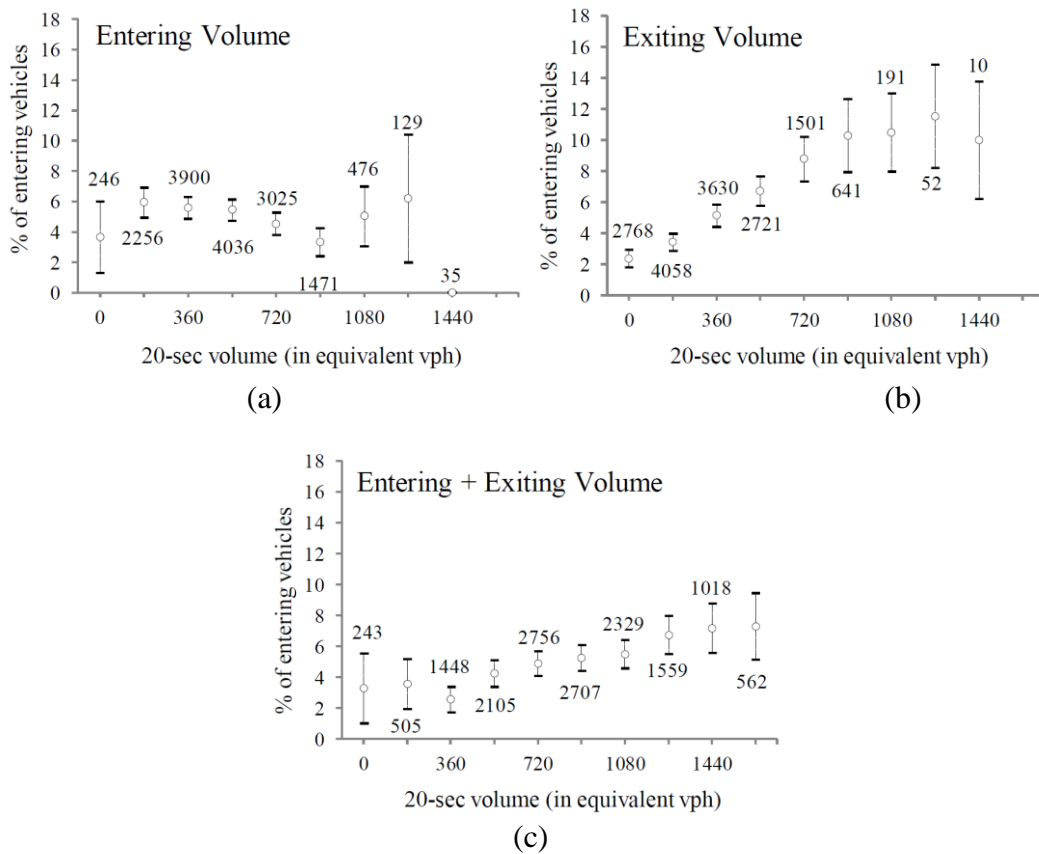
Figure 4.6. Means plots of observed priority abstaining behavior as a percentage of entering vehicles with number of observations.

This research paper presents a data collection, processing, and reduction methodology to examine non-compliant behavior from video observations of single-lane roundabout entries. This event-based timestamp approach allows for direct correlation to time-specific volume levels. In order to make an assertion about the effect of a certain type of driver behavior or action, one

must also know the interactions with and resulting behavior of the surrounding vehicles in both the entering and circulating streams. In addition, the processing methodology allows for a quantitative analysis of stopped delay for the entering vehicle stream.

The findings of this research show that priority taking and priority abstaining occur at *all* volume levels. In reality, priority taking and periods of momentary priority reversal occur at very low volumes, counter to what is presented in current literature. Priority taking was found to be positively correlated with circulating volume. It should also be noted that there are two very distinct types of priority taking. When circulating traffic is very high one can expect people to become frustrated and drive in to a gap that is too small (Troutbeck, R. & Kako, 1999; Kimber, 1980), which generally occurs at low speeds. Alternatively, one may incorrectly judge the size of a gap or drive straight in without looking, not knowing they were supposed to yield – both of which generally happen at higher speeds. Priority abstaining was observed even when there were no circulating or exiting vehicles. Priority abstaining behavior is positively correlated with exiting volume, but may be negatively correlated once sustained exiting flows are reached.

These non-compliant types of behavior clearly cause additional delay unaccounted for in existing models and should be considered at roundabouts. It is also apparent that frequency of priority abstaining behavior diminishes with time, although not completely. Priority taking behavior, however, appears to remain unchanged with respect to time since construction. These findings suggest that in addition to gaps that drivers accept becoming smaller over time (Mensah, S., Eshragh, S., & Faghri, A., 2010), aggressive-type incorrect negotiations remain constant while conservative-type incorrect negotiations of drivers are reduced.

There are five notable issues with gap-acceptance and car-following methodologies when considering entry driver behavior at roundabouts:

1) For priority abstaining there is no gap by which to measure accepted or rejected and no lead vehicle for it to follow. This behavior also causes queues by blocking other entering vehicles even when there are no vehicles in the circulating stream.

2) Priority abstaining behavior suggests that drivers are making judgments on gaps further upstream than where current practice has them being measured.

3) Gap acceptance models describe vehicle interactions in a **reactive** manner – describing only the behavior of entering vehicles based on how they react to major stream gaps. Priority rules at roundabouts are less strict and the relationship between major stream and minor stream is much more **interactive**.

4) There is no information regarding the *utilization of space* by the entering vehicle (e.g., the gap was accepted but there was impedance to the follow-up vehicle) when using an accepted/rejected gap framework. Priority taking also causes an *immediate alteration* of the gap into which the vehicles enters. The headway measured between circulating vehicles is different than the actual headway when an entering vehicle *goes when it should not.* The gap is still measured between the same two circulating vehicles, but the second circulating vehicle has assumed a slower secondary velocity because of the entering drivers' forcing behavior (i.e., measured accepted gaps have been artificially

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inflated and those artificially inflated gap values are going to occur more often as traffic volume increases).

5) Priority taking and priority surrendering cause backups in the circulating stream that, even at lower volumes, spillback and affect upstream approaches on the roundabout. This brings into question the validity of the longstanding assumption that roundabout approaches can be analyzed independently of each other (Kimber & Semmens, 1977).

This research adds to the understanding of roundabout operations and entry driver behavior by using observations of real-world driver interactions at roundabouts. This represents timely research with regard to the ways in which driver behavior type and frequency change under prevailing traffic conditions. Further, current modeling methods do not appropriately account for driver behavior that does not conform to gap acceptance frameworks or the offside-priority rule (i.e., yield-at-entry) at roundabouts. These findings provide the foundation for and will are used in further research to develop improved models that explicitly account for non-compliant types of behavior in traffic simulation.

5. Simulation of Priority Taking and Abstaining Using Cellular Automata

This chapter summarizes the work published and/or presented in the following references:

Belz, N.P., Aultman-Hall, L., Montague, J. (April 2014). *Cellular Automata and the Influence of Driver Behavior at Roundabouts*. 4th International Conference on Roundabouts, Seattle, WA.

Belz, N.P. (January 2013). *Operational and Planning Models for Single-Lane Roundabouts*, 92nd Annual Meeting of the Transportation Research Board of the National Academies, Workshop 103 – Doctoral Student Session in Transportation Operations and Traffic Control, Washington D.C.

Traffic rules at a roundabout dictate that the circulating stream of traffic has priority over the entering streams of traffic, referred to as the offside-priority rule. The lack of a rigidly defined traffic control at roundabout entries, however, elicits a range of driver behavior including behaviors that do not comply with the offside-priority rule. Although these non-compliant types of behavior are inconsistent with existing traffic theory, they can be regularly observed in the field. Further, current capacity and operational models for roundabouts may be inadequate as they fail to account for all types of roundabout driving behavior.

The stochastic and dynamic nature of driver behavior when entering a roundabout makes a cellular automata (CA) model the ideal platform for a scenario evaluation of behavioral impacts on overall roundabout performance. CA approaches have been shown to be particularly useful for modeling transportation systems (Helbing & Nagel, 2004; Balmer, et al., 2004), phase transitions in traffic flow (Kerner & Rehborn, 1997), nonlinearity with respect to traffic congestion (Orosz, et al., 2009; Vlahogianni, et al., 2011), and self-organized routing (Yerra & Levinson, 2005; Levinson & Yerra, 2006). This work builds on past research and applications of CA for roundabout traffic simulation (Chopard, Dupuis, & Luthi, 1998; Wang & Ruskin, 2002). CA models are particularly useful for analyzing complex interactions by breaking systems down into their most basic parts. This research focuses on vehicle-vehicle interactions rather than focusing on individual vehicle dynamics as proposed in past CA research (Dupuis & Chopard, 2003; Wang & Ruskin, 2002; Chopard, et al., 1998). A cellular automata (CA) model is developed and validated against real-world data to evaluate the relative influence that priority taking and priority abstaining behavior have on capacity, delay, and queue length at single-lane roundabouts. The distinct difference in this research is that the circulating stream is never guaranteed priority and entering behavior types other than those based on gap-acceptance are allowed.

Although priority taking and priority abstaining entry behavior have been observed at roundabouts, it is apparent that current methodologies do not explicitly account for these types of behavior. This finding motivates three research objectives. First, a new CA model, Cellular Automata for Roundabout simulation (C.A.Rsim), is developed that allows for priority taking and priority abstaining while also allowing for priority reversal. Priority reversal occurs when multiple vehicles enter from the approach while the circulating stream remains stopped. Second, the C.A.Rsim model is calibrated based on observed levels of priority taking and priority abstaining behavior collected at five roundabouts in Maine, New Hampshire, Vermont, and New York. The model is also validated against existing models of roundabout capacity. Finally, the impact of priority taking and priority abstaining on roundabout performance is quantitatively assessed using C.A.Rsim. These results provide insight on how variations in conflicting flow

(i.e., traffic volume and turning movement balance) impact the amount of observed non-compliant behavior. The impact of reduced levels of priority abstaining at older roundabouts is also assessed.

The model presented here is a CA model with stochastic arrival, turning movement, and driver behavior assignment. The C.A.Rsim model is presented as a two-speed (zero and non-zero) two-dimensional cellular automata model. For simplicity, only one type of "vehicle" is considered and thus speed and movement are deterministic. The four-legged roundabout is comprised of eight one-dimensional deterministic CA which represent the approach and exit legs, and one intersecting CA ring (see Figure 5.1a). Each time step in the model represents one second of real time. Direction of movement and cell adjacency are defined in a *connectivity matrix* (see Figure 5.1b) which uses cell numbers (see Figure 5.1a) to determine which cell can be reached from the current cell. The first row *(current cell)* represents the cell that a vehicle would be occupying in one time step, the second row *(next cell 1)* represents the next adjacent cell that a vehicle could move to in the next time step, and the third row *(next cell 2)* represents the cell the vehicle can move to in the next time step when merging or diverging to/from the circulating ring.
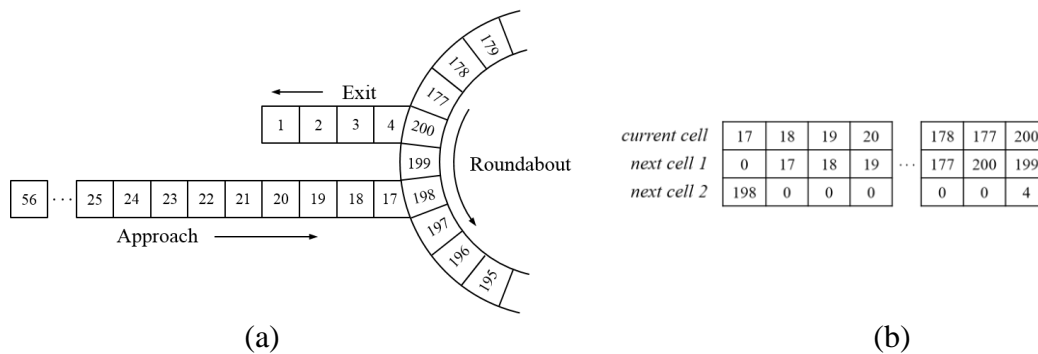
Figure 5.1. (a) Cellular representation of a roundabout, approach, and exit leg with cell numbers and arrows denoting direction of traffic flow with (b) an example of the connectivity matrix.

In general, update rules for simple cells are: if there is a vacant cell in front of an occupied cell, the vehicle will move forward one cell in the next time step (see vehicle *n* and *k* in Figure 5.); if a cell is occupied by a moving vehicle, the following vehicle will move forward in the next time step (see vehicles *m* and *l* in Figure 5.); or if there is a cell occupied by a stationary vehicle, a following vehicle will become or remain stationary in the next time step (see vehicles *j* and *i* in Figure 5.). The cell that a vehicle needs to check before moving is determined from the connectivity matrix (Figure 5.1b).
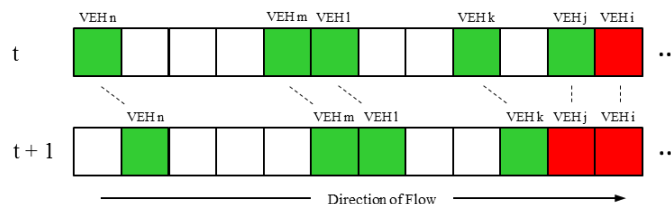
Figure 5.2. Update rules for simple cells with moving (green) vehicles and stationary (red) vehicles.

Priority abstaining behavior is represented by a vehicle that stops in the entry cell when the next upstream diverge cell is occupied. Figure 5.3 illustrates a case where a priority abstaining vehicle (see PA $_t$ in Figure 5.3a) moves into the entry cell, finds the *diverge cell* occupied, and comes to a stop (see PA $_{t+1}$ in Figure 5.3b). This mimics the nature of priority abstaining where a driver yields to a vehicle that intends to exit. Priority abstaining vehicles require two empty cells (in addition to the merge cell) in order to enter.

(a)   (b)
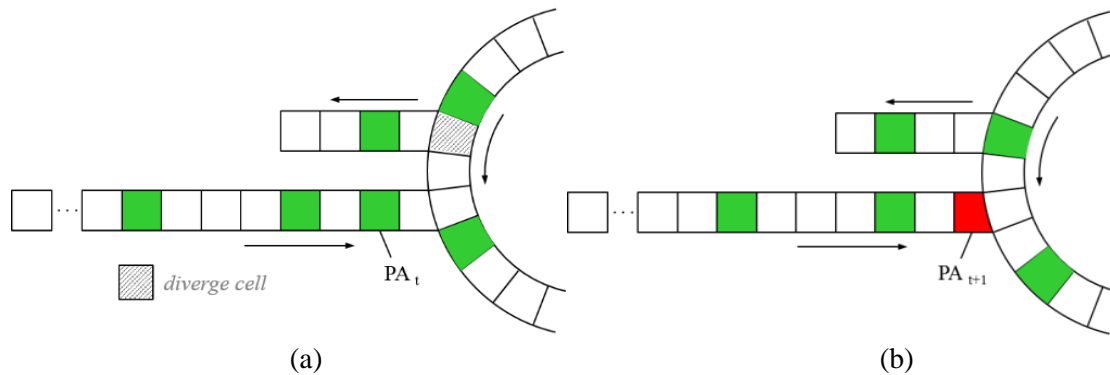
Figure 5.3. Priority abstaining demonstrated in two sequential CA time steps with moving (green) vehicles and stationary (red) vehicles.

Priority taking behavior is represented by a vehicle that enters the roundabout when the merge cell is open regardless of whether the next upstream cell is occupied (see PT $_t$ in Figure 5.4a). This behavior causes the circulating vehicle to stop (see the *red* vehicle upstream from PT $_{t+1}$ in Figure 5.4b).

(a)   (b)
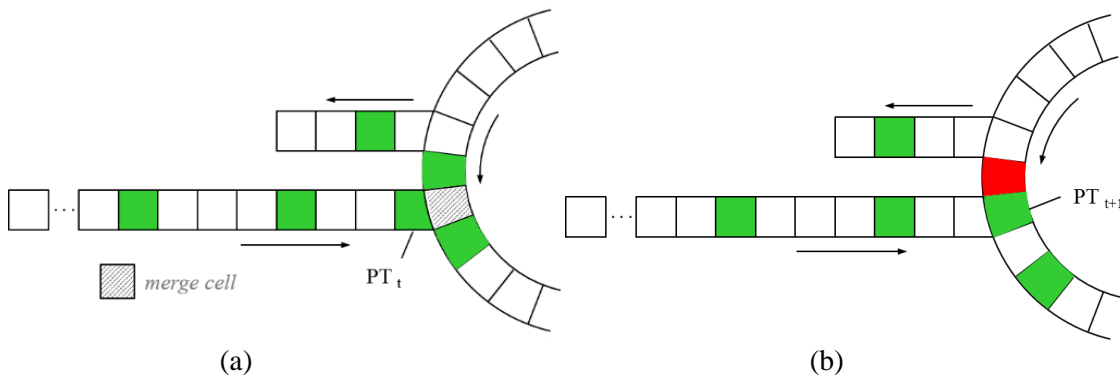
Figure 5.4. Priority taking demonstrated in two sequential CA time steps with moving (green) vehicles and stationary (red) vehicles.

The C.A.Rsim model was calibrated against field video data collected at five roundabouts spanning the northern New England region (Maine, New Hampshire, Vermont, and New York). This data provided a total of 1108 observations of priority abstaining behavior and 337 observations of priority taking behavior at varying traffic volume levels. The likelihood of priority taking and priority abstaining behavior occurring increases as conflicting volume increases (refer to Section 4). The entry behavior of vehicles coded with priority taking or priority abstaining behavior was recorded to determine if they actually exhibited that behavior at

entry. For instance, a "priority taker" may reach the entry at a point when a circulating vehicle is too far back to be affected; hence the entry behavior appears rational instead. The observed vehicle behavior totals in the simulation were consistent with driver behavior observed in the field when 20% of the generated vehicles were coded with priority taking behavior and 20% were coded with priority abstaining behavior (see Figure 5.5). Only a slight discrepancy was observed for the priority taking behaviors (see Figure 5.5b), but overall results matched the field data well.
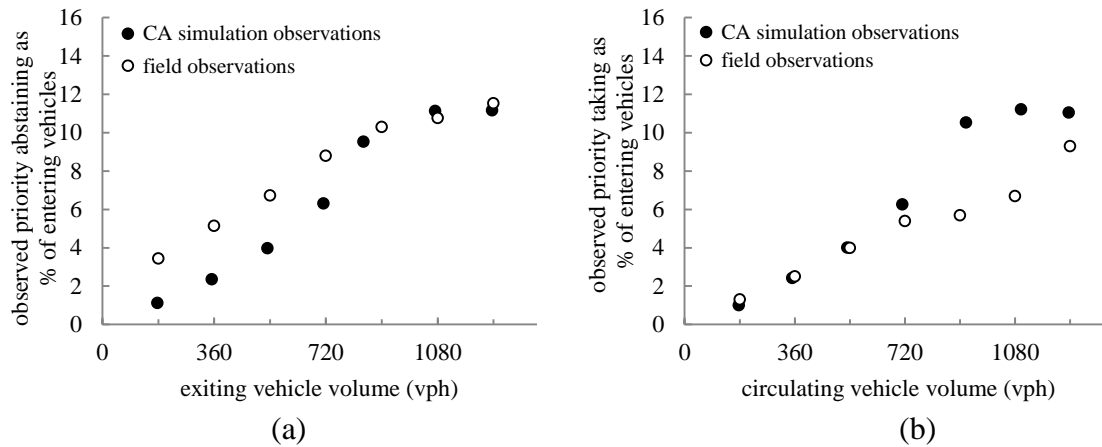
Figure 5.5. Comparison of observed vehicle behavior percentages compared to conflicting traffic volume for (a) priority abstaining and (b) priority taking behavior both coded at 20% of generated vehicles.

The calibrated model results are compared to other models in Figure 5.6. The discrepancy at higher volumes (approaching and above a circulating flow rate of approximately 1400 vph) in the calibrated model is hypothesized to be a result the nature of priority taking behavior which creates jamming within the circulating ring and impacts upstream legs. As a result, overall entry capacity (i.e., when considering all four legs) is reduced. This makes the C.A.Rsim model more accurate when analyzing the entire roundabout as a unified system as compared to existing models. Using the calibrated model with 20% of the vehicles coded with priority taking and 20% of vehicles having coded with priority abstaining behavior, the following research questions are addressed: 1) how do variations in conflicting flow (i.e., traffic volume and turning movement balance) impact the amount of observed priority taking and priority abstaining behavior; and 2) how does the reduction of priority abstaining observed at an older roundabout impact overall roundabout performance?

Left-heavy scenarios produce more conflicting circulating vehicles for priority taking while right-heavy scenarios produce more conflicting exiting vehicles for priority abstaining. Under right-heavy scenarios, vehicles will spend less time in the circulating ring and fewer vehicles will be circulating through a merge cell. In right-heavy scenarios, a higher percentage of priority taking (Figure 5.7a) occurs at any given volume level because exiting vehicles create new openings for priority takers to enter into. Otherwise, jams and bunching formed by a previous priority taker will generally inhibit anyone from entering except for the case of priority reversal (i.e., multiple priority taking vehicles arriving in a row).
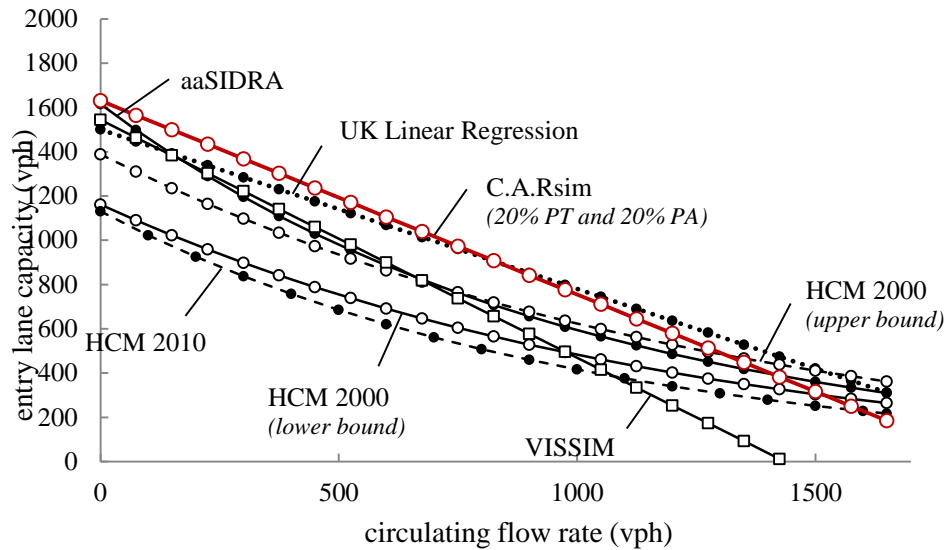
Figure 5.6. Comparison of capacity estimates for C.A.Rsim with 20% priority taking (PT) and 20% (PA) priority abstaining against existing models with default parameters for a typical single-lane roundabout.

Also under right-heavy scenarios, more vehicles are able to enter the roundabout meaning that even though a larger number of vehicles exhibit priority abstaining behavior, the percentage of vehicles exhibiting priority abstaining behavior is lower as compared to the other turning movement scenarios. In left-heavy scenarios, fewer vehicles have the opportunity to enter the roundabout overall. In other words, the percentage of priority abstaining behavior which is exhibited will be higher (see Figure 5.7b). In addition to traffic volume, variations in conflicting volume caused by turning movement balances impact the frequency of observed non-compliant behavior.

The results of Section 4 suggest priority abstaining behavior diminishes by about 50% once a roundabout has been in place for more than five years and drivers are more familiar with proper roundabout navigation. Figure 5.8 presents a comparison of the calibrated model coded with 20% priority taking and 20% priority abstaining vehicles with a model coded with 10% priority abstaining vehicles. As one might expect, reducing the number of vehicles coded as priority abstainers by half also reduced the observed percentages by approximately half (see Figure 5.8a). Significant differences in average system delay per time interval (see Figure 5.13b) are seen between arrival rates of 720 vph and 1080 vph on all four approaches *(p < 0.001)*. The largest difference of 933 seconds (approximately 15 minutes) occurs at an arrival rate of 900 vph on all four approaches. The average system delay per time unit for the counter factual model is also shown for reference. In addition, there are significant differences in average queue length at arrival rates of 900 and 990 vph *(p < 0.001).* These findings illustrate how non-compliant behavior impacts roundabout performance and how that performance is likely to change once drivers become more familiar with roundabouts.
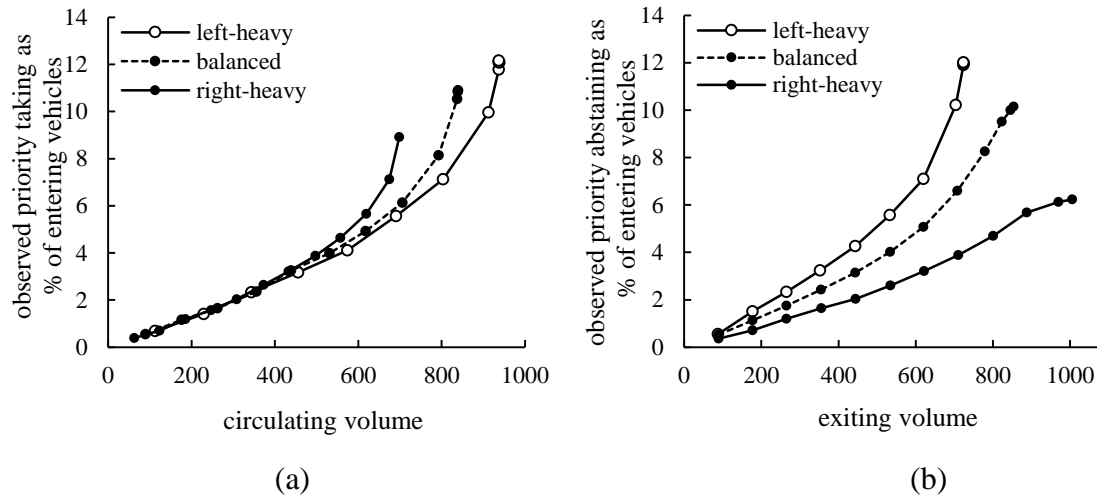
Figure 5.7. Comparison of observed entering vehicle behavior percentages compared to conflicting traffic volume for (a) priority taking behavior and (b) priority abstaining behavior under different turning movement scenarios.

The C.A.Rsim model presented in this research is more parsimonious than many existing microsimulation models. The results provide insight on how variations in conflicting flow (i.e., traffic volume and turning movement balance) impact the amount of observed non-compliant behavior. On a microscopic level, the model is able to reproduce known real-world phenomena such as priority reversal and allows us to answer new questions related to non-compliant types of driver behavior. Imposing a slow-to-start rule in the circulating ring allows the jamming effect (i.e., queues that form and block upstream approaches of the roundabout) caused by priority taking vehicles to be simulated.

The results also reinforce the idea that not all vehicles that are "predisposed" to have a certain type of behavior will necessarily exhibit that behavior. Whether or not a vehicle that has the potential for priority taking or abstaining behavior will actually be observed to undertake these maneuvers, which is dependent upon the traffic conditions in the circulating ring when entering. At higher traffic volumes when it may be harder to enter the roundabout, drivers are more likely to encounter the conditions under which a particular behavior can be exhibited. That being said, the model suggests that the driver population in New England is comprised of approximately 20% drivers with the potential for priority taking and approximately 20% drivers with the potential for priority abstaining behavior.

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(a)

(b)

(c)
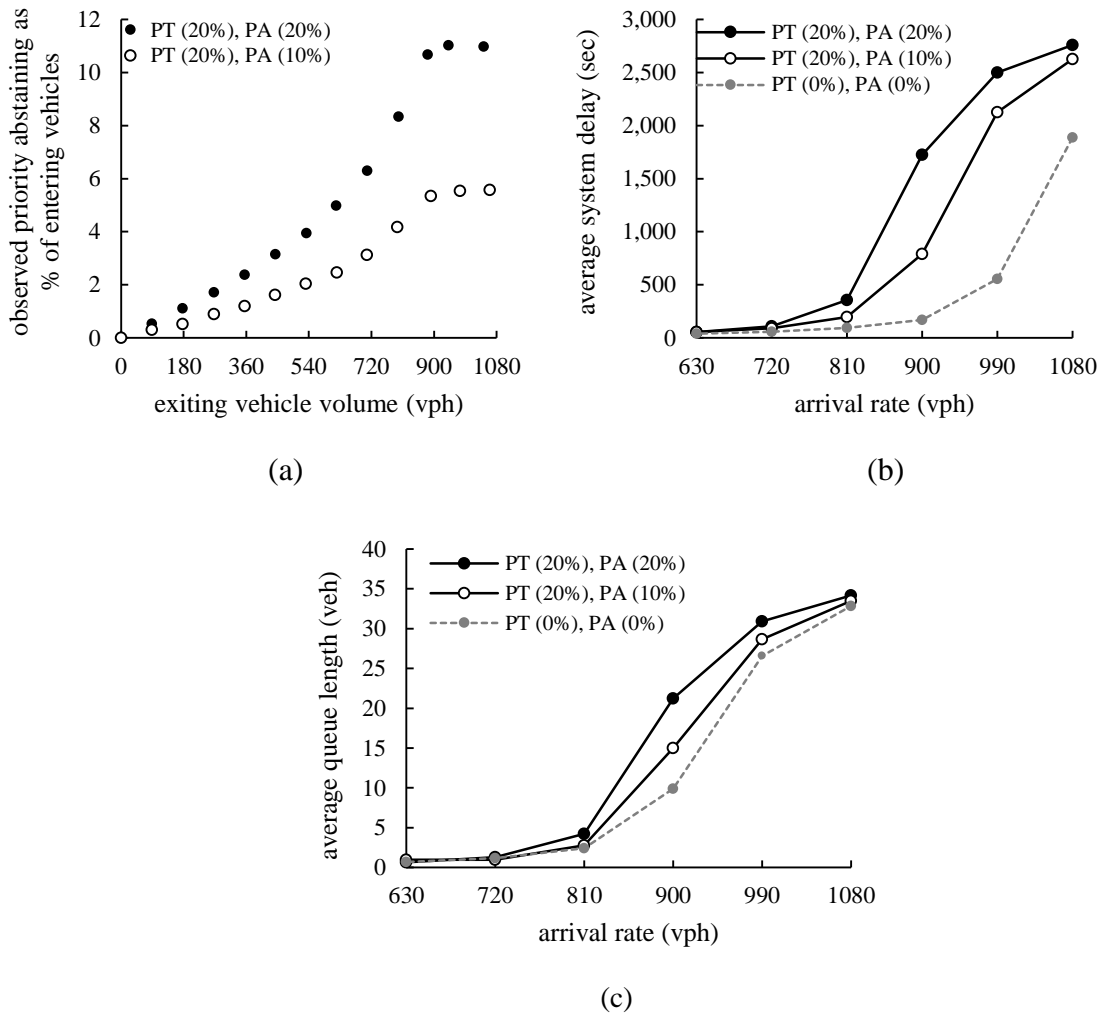
Figure 5.8. Comparison of (a) observed entering vehicle behavior percentages compared to conflicting traffic volume for priority abstaining behavior, (b) average system delay, and (c) average queue length per time interval in the calibrated model versus the reduced model.

The C.A.Rsim findings suggest that current models overestimate capacity at high circulating volumes. This is corroborated by prior research (Akcelik, 2003; Hagring, 2000). Consequently, these models also overestimate overall system delay at low volumes and underestimate delay at high volumes. C.A.Rsim is also able to accurately represent priority reversal (i.e., the transfer in priority between the circulating and entering traffic streams) which reduces overall capacity of the roundabout. Results also show that the reduced amount of priority abstaining behavior that occurs at older roundabouts can significantly reduce queue lengths and system delay at certain traffic volumes. Further, certain turning movement balances impact the amount of priority taking and abstaining behavior which occurs. While not accounting for priority abstaining behavior, existing methods also fail to consider observed reductions in this behavior type as drivers become more familiar with roundabout negotiation. These results suggest a need for driver education and behavior change to improve the capacity of roundabouts.

6. Conclusions

The method presented in this research represents a new innovative approach that integrates multiple forms of data spatially to identify spatial, temporal, built-environment, and social characteristics of areas where technically-feasible roundabouts have not being built. This research highlights the challenges facing roundabout implementation in northern New England which are distinctly different from other regions in the United States and warrant further research.

A new framework for describing non-compliant types of driver behavior (i.e., priority taking, abstaining, and surrendering) was created and a new method for extracting these behaviors from video of real-world driver interactions is developed. The collection and processing of these videos also contributes new data of driver behavior and roundabout operations that can be used in subsequent research. Section 4 represents timely research with regard to the ways in which driver behavior type and frequency are impacted by non-geometric factors such as prevailing traffic conditions and driver familiarity. Findings also provide a foundation for the microscopic simulation and modeling methodology presented in Section 5.

A new cellular automata model (C.A.Rsim) is developed to simulate traffic at a roundabout and evaluate the impact of these types of behavior on roundabout performance (e.g., capacity, queue length, and delay). Calibration and validation is conducted using real-world field data collected as part of research presented in Section 4. Although not expected to be a complete substitute for more detailed approaches, this research provides a parsimonious model that produces capacity and performance analysis results similar to those of exiting methods. In addition, this research advances the use of cellular automata methods for transportation applications.

The research on roundabout implementation trends will be expanded by including more data on abandoned technically feasible roundabout projects with a larger spatial coverage and areas with higher roundabout conversion rates. Survey data will also be incorporated to account for subjective measures of attitudes and values about transportation and neighborhood setting.

The findings related to priority abstaining behavior suggests that drivers are making judgments on gaps further upstream than where current practice has them being measured. Future work will explore whether there is a more appropriate location to measure headways in a roundabout that are used in gap analyses. This research will also be expanded beyond the New England region; regional variations in driving styles may affect the nature of non-compliant behavior. Multilane roundabouts should also be included in the locations where data are collected to determine if the findings translate to larger roundabouts with additional lanes.

The C.A.Rsim model will also be further developed to include a multi-speed model, additional non-compliant behaviors, and varying roundabout diameters. In addition, field data will be collected to explore the difference between priority taking and priority sharing (i.e., selfish and collective behavior) and possibly incorporated into the C.A.Rsim model.

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