Evaluation of Roundabout-Related Single-Vehicle Crashes

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Roundabouts reduce fatal and injury crashes at intersections when converted from other intersection control types. In Wisconsin, roundabouts have been linked to a 38% decrease in fatal and injury crashes. Part of this reduction can be attributed to crash types that result in the mitigation of more serious injuries. However, the reduction comes at a cost because other crash types, such as single-vehicle collisions, may increase. Six years of crash data on 53 roundabouts in Wisconsin were examined for crash causes and geometric characteristics that affected single-vehicle crashes. Weather and impaired driving, particularly by younger drivers, were primary causes for more than half of all single-vehicle crashes at the study roundabouts. Younger drivers (18 to 24 years of age) were involved in a significantly higher proportion of single-vehicle crashes than the total proportion of licensed drivers in that age group. Younger drivers were involved in approximately one-third of all crashes that involved impaired driving and in two-thirds of all speed-related single-vehicle crashes. A negative binomial model was constructed to estimate run-off-road crashes at approaches. It was found that roundabouts with higher approach speeds and higher traffic volumes experienced more run-off-road crashes. Landscaped central islands experienced significantly lower frequencies of run-off-road crashes.

Roundabouts are an increasingly common alternative to stop- and signal-controlled intersections in the United States and around the world. As of 2014, an estimated 3,200 roundabouts were installed in the United States (*1*). Their recent popularity is the result primarily of the operational and safety benefits that roundabouts provide. Operationally, roundabouts have been associated with a decrease in delay, queue length, congestion, and degree of saturation when compared with other control types (*2, 3*). Roundabouts can lower electricity and maintenance costs and improve traffic flow for users. In addition, roundabouts are an aesthetically pleasing alternative to intersection control types.

Roundabouts have a large impact on traffic safety. Roundabout design improves safety by requiring drivers to reduce speeds as they navigate the intersection and to reduce the number of conflict points from 32 to eight for a four-legged intersection (Figure 1*a*), and 11 to six for three-legged intersections (Figure 1*b*) (*4–7*). The unique geometry of a roundabout provides a safety benefit by reducing the likelihood of maneuvers that frequently result in high-severity crashes. Given these geometric features, roundabouts have been shown to reduce fatal and injury crashes by more than 90% when converted from other intersection control types (*6*).

In Wisconsin, more than 300 roundabouts currently are installed, approximately 10% of all roundabouts in the United States. Similar to national trends in roundabouts, Wisconsin's roundabouts have led to a large reduction in fatal and injury crashes. In a study of 30 roundabouts that were converted from stop- and signal- controlled intersections, fatal and injury crashes were found to have decreased by 38% (*8, 9*). Nonetheless, total crashes increased by 12%, despite the large reduction in fatal and injury crashes. Although the reduction in fatal and injury crashes is a positive step toward safer intersections, there is still room for improvement. The increase in total crashes, particularly property-damage-only crashes, suggests a need for further research.

Although research has shown that the design of roundabouts reduces the severity of crashes, some research has found an increase in total crashes. The reduction in severe crashes has resulted in part from the mitigation of high-severity crash types by the geometric constraints of the roundabouts. This reduction comes at a cost, however, because other crash types become more prominent. One crash type (i.e., single-vehicle run-off-road crashes) was found to account for approximately 30% of crashes at single- and multilane roundabouts (*10*). Given the call published in *NCHRP Report 672: Roundabouts: An Informational Guide*, 2nd ed., for continuing research to further understand and improve issues with roundabout safety and the high frequency of single-vehicle crashes at roundabouts, the mitigation of such crashes and the reduction in their severity are paramount to further improvement in roundabout safety (*7*).

LITERATURE REVIEW

Roundabout Safety Benefits

According to FHWA, intersections account for up to 23% of fatal and 50% of serious injury crashes in the United States (*11*). One targeted countermeasure given by FHWA to reduce intersection-related crashes is the conversion of intersections to roundabouts (*12*). The conversion to roundabouts has been shown to reduce fatal and injury crashes significantly. Robinson et al. found a reduction in injury crashes of 51% in the United States (*13*). Similar results were found in other countries: Australia, France, and the United Kingdom had injury reductions of up to 87%, 78%, and 39%, respectively. Retting et al. reported a reduction of 76% in injury crashes in the United States (*14*). Numerous other studies from the United States and around the world have found significant reductions in injury crashes

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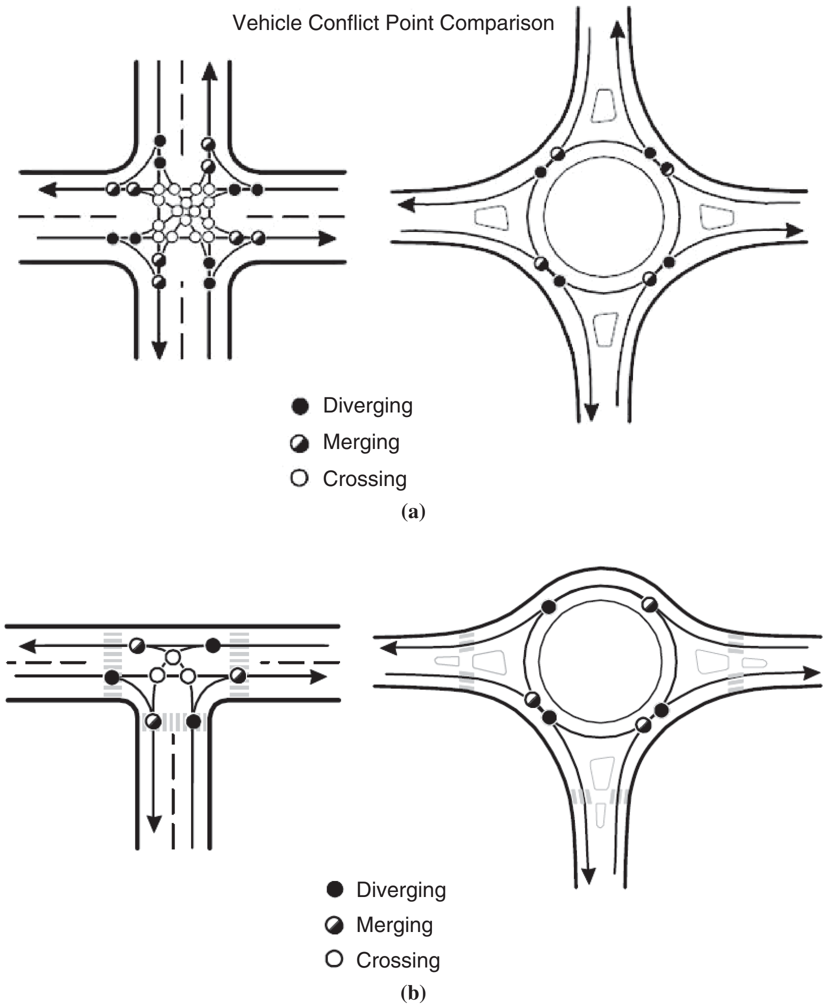


FIGURE 1 Conflict point diagrams: (*a*) four-legged intersection and (*b*) three-legged intersection (*7*).

(*15–17*). However, crash frequencies for property-damage-only crashes have been mixed.

Common Crash Types at Roundabouts

Crash types common at other intersection control types do not occur at roundabouts frequently. Given roundabout geometry, vehicles travel in the same direction and at a lower speed than they do at other intersection types, which makes the crashes that do occur less severe (*8*). Lower speeds and travel in one direction mitigate head-on, right-angle, and left-turn-related collisions, which in general are more severe than other crash types. A study of 39 roundabouts throughout the United States found entering–circulating, exiting–circulating, and rear-end crashes to be the most frequent crash types (*18*). Single-lane roundabouts had a higher number of entering–circulating crashes, whereas multilane roundabouts had a higher number of exiting–circulating crashes. A study of 17 roundabouts throughout Kansas, Maryland, Minnesota, Oregon, and Washington found a significant decrease in angle, head-on, and rear-end crashes (*19*). Sideswipe crashes and single-vehicle fixed-object collisions increased significantly, however, and were the most common crash type at the study roundabouts.

Single-Vehicle Crashes

Single-vehicle crashes are responsible for a large portion of fatal and injury crashes. In 2014, 17,885 single-vehicle fatal crashes were reported in the United States (*20*). Single-vehicle run-off-road crashes have been found to be associated with speeding, roadway alignment, impaired driving, and adverse weather (*21*). Eustace et al. found road condition to be the most important factor to affect the severity of run-off-road crashes (*22*).

Single-vehicle crashes were found to make up between 30% and 50% of crashes at single-lane roundabouts and 28% to 30% at multilane roundabouts (*10, 23*). In a study of high-speed rural roundabouts, Isebrands found that, when intersections were converted to roundabouts, single-vehicle fixed-object collisions increased by 320% (*19*). Single-vehicle run-off-road crashes that involved a vehicle collision with the central island as a result of unsafe speed accounted for nearly half of all single-vehicle run-off-road crashes (*24*). Steyn found several trends related to single-vehicle crashes, including impaired driving, motorcycles, single-vehicle crashes with the central island, and excessive speed (*25*). In NCHRP Report 672, single-vehicle crashes at roundabout approaches were found to be associated with sharp entry curves (*7*).

SITE SELECTION AND DATA COLLECTION

More than 300 roundabouts currently are installed in Wisconsin. To ensure that enough crash data were available, only roundabouts constructed in 2008 or beforehand were candidates for this study. Crash data were analyzed from the year after roundabout construction (i.e., 2009), until the most recent year that crash data were available (i.e., 2014), for a total of 6 years of crash data. Only roundabouts located on the state trunk network were chosen for analysis, given the lack of data on roundabouts not on the network. Roundabouts were omitted from the study if there was additional construction after 2008, or if the roundabouts were too closely spaced with another intersection other than a roundabout. Roundabouts closely spaced to another intersection control type were removed because of the possible effect these other intersections might have on the roundabout. After the selection of roundabouts with enough crash data available that also met the other selection criteria, 53 roundabouts remained in the study, which represented all regions in Wisconsin. The locations of the study roundabouts can be seen in Figure 2. The 53 roundabouts included urban and rural roundabouts, as well as high-speed and low-speed approaches. Posted speeds of 45 mph or higher are considered by the Wisconsin Department of Transportation, Madison, to be high-speed roundabouts for design purposes in the *Facilities Development Manual* (*26*).

The study collected 6 years of crash data from WisTransPortal, a web-based application that maintains all crash data for the state (*27*). In total, 1,467 crashes were reported at the 53 study roundabouts. Single-vehicle crashes accounted for 413 (28.2%) of these crashes, similar to findings in previous research in Wisconsin (*10*). Two fatal single-vehicle crashes were reported at the roundabouts: one involved the ejection of a driver from a vehicle in inclement weather, and the other involved an impaired driver on a motorcycle. Of the injuries identified, 11 were incapacitating injuries (KABCO A), 46 nonincapacitating injuries (B), 19 possible injuries (C), and 335 were property-damage-only crashes. Single-vehicle crash reports were analyzed and categorized on the basis of the type of single-vehicle crash that occurred, where the crash occurred within the

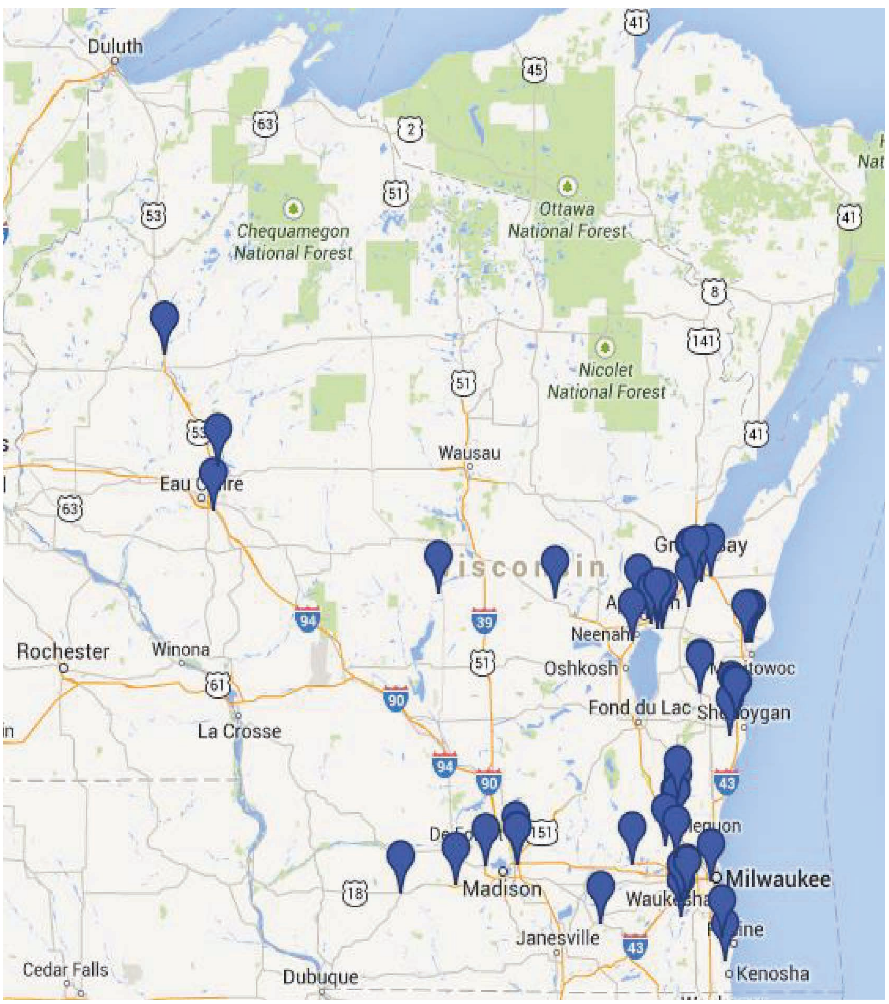


FIGURE 2 Study locations of roundabouts.

roundabout, the cause of the crash, and the age of the driver involved. In addition, a model on the basis of geometric characteristics was constructed to estimate run-off-road crashes.

CRASH CHARACTERISTICS

Single-Vehicle Crash Causes

Single-vehicle crash causes were determined, when possible, from the crash reports. Each crash report narrative, diagram, and crash cause noted by the reporting officer was examined. Causes were determined for 337 (81.6%) of the crashes. A cause was not determined for 76 crashes. Either they were hit-and-run single-vehicle crashes, or else not enough information could be discerned from the crash report to determine a cause. Crash causes were categorized into the following 10 major groupings, inductively determined through the examination of each crash report:

- Impaired driving (e.g., alcohol or drug use or medical conditions);
- Weather-related crashes (e.g., ice- or snow-covered roads, heavy snow, or fog);
- Animal-related crashes;
- Driver distraction-related crashes (e.g., cell phone use, talking with passengers, distraction outside the vehicle, or smoking);
- Vehicle failure or malfunction (flat tire or vehicle stalled);
- Road surface condition (other than weather related);
- Trailer related (trailer overturn or trailer run-off-road);
- Avoidance of noncontact vehicle;
- Driver inexperience or inadequate driving training; and
- Speed related.

Figure 3 shows the proportion of total crashes for each crash cause, as well as the proportion of injury crashes for each crash cause.

Weather conditions were the most frequent cause of single-vehicle crashes, accounting for 34.6% of single-vehicle crashes, followed by impaired driving (19.4%). Together, weather and impaired driving were responsible for more than half of all single-vehicle crashes reported. Only four impaired-driving-related crashes also involved inclement weather. Avoidance of a noncontact vehicle was the cause of 6.8% of single-vehicle crashes. These crashes involved (*a*) vehicles that swerved to avoid collision with another vehicle and (*b*) vehicle departures from the roadway, vehicle overturns, or both. Speed, road conditions, and trailer-related single-vehicle crashes were each the cause of approximately 5% of single-vehicle crashes.

Fatal and injury crashes had different causes. Weather-related crashes were responsible for 34.6% of single-vehicle crashes, but only for 14.1% of fatal and injury crashes, which suggested that most weather-related crashes were not serious in nature. Crashes related to the road condition and avoidance of a noncontact vehicle involved higher proportions of fatal and injury crashes than the overall proportion of crashes. These crashes involved motorcycles that overturned as a result of the crash cause. More than three-fourths (77.8%) of overturned crashes related to the road condition or to the avoidance of a noncontact vehicle that resulted in injury. Speed-related single-vehicle crashes also were associated with a higher proportion of injury crashes (i.e., 11.5% of fatal and injury-related crashes resulted from speed, whereas only 5.8% of all single-vehicle-related crashes did). This result was unsurprising, given that higher speeds in general lead to less safe roadways.

Single-Vehicle Crash Type

Single-Vehicle Run-off-Road Crashes

Run-off-road collisions were the most frequent kind of single-vehicle crash observed, accounting for 86.7% of crashes. Run-off-road crashes included any vehicle that collided with a fixed-object not in the roadway, or vehicles that left the roadway entirely. Most (55.3%) of run-off-road collisions occurred at a roundabout approach,

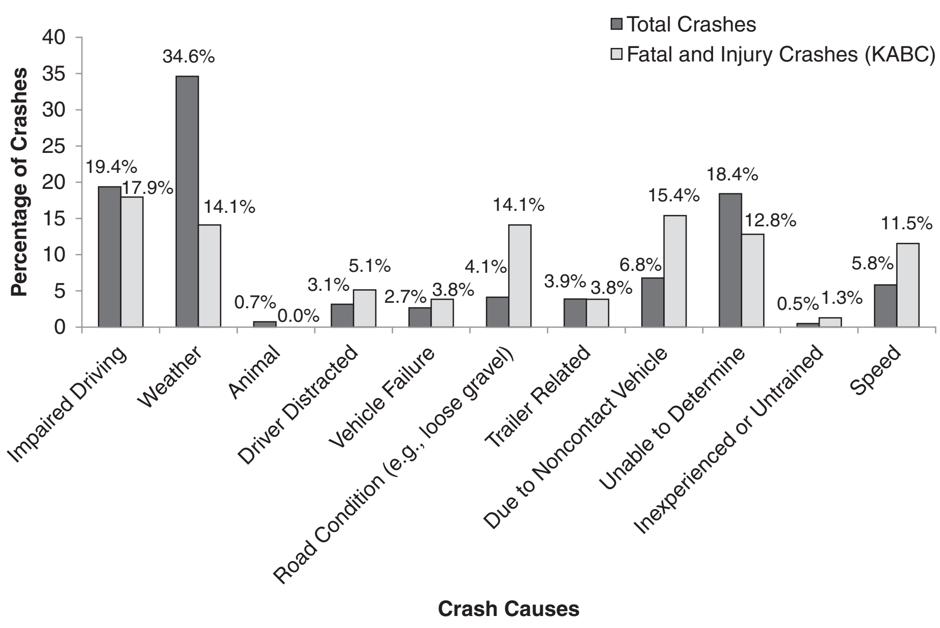


FIGURE 3 Crash causes for total crashes and fatal and injury crashes.

whereas 38.8% occurred within the circulating lanes, and 6.7% occurred in the exiting lanes of a roundabout. Nine (2.5%) of the run-off-road collisions involved a truck.

A plurality (39.5%) of run-off-road collisions was weather related. Of the weather-related run-off-road collisions, 55.8% occurred at a roundabout approach, 39.9% within the circulating lanes, and 4.3% at the roundabout exit. The high volume of weather-related run-off-road collisions highlighted a problematic aspect with respect to roundabout safety. As people become more familiar with roundabouts, weather-related crashes continue to occur at high frequencies.

Impaired driving was the cause of 21.8% of run-off-road collisions. Approximately half (48.7%) occurred at the roundabout approaches and 47.4% within the circulating lanes. Together, weather and impaired driving accounted for nearly two-thirds (61.3%) of run-off-road collisions. Although impairment or weather conditions were the primary causes of these crashes, they were not likely to have been solely responsible for the high frequency of run-off-road collisions. The unique geometry and operating characteristics of a roundabout compounded by impairment or weather conditions increased the likelihood of a run-off-road collision at a roundabout.

Single-Vehicle Overturn Crashes

Vehicle overturns accounted for 13.1% of single-vehicle crashes. The overturn-related crashes occurred as the result of a motorcycle or of a tractor trailer overturning. Most (81.8%) overturn crashes occurred within the circulating lanes. Only 12.7% of crashes occurred at an approach and 5.5% at the exit of a roundabout.

Of the overturn crashes, 14.5% were trailer related. All truck-related overturns occurred within the circulating lanes. These crashes reveal the difficulty that some trucks have in navigating a roundabout, either because of speed, geometry, or their combination. The remaining overturn crashes were related to motorcycles. Weather conditions and road conditions were the cause of 38.3% of motorcycle overturns. Avoidance of a collision with a noncontact vehicle was the cause of 29.8% of motorcycle overturns.

In total, there were 47 motorcycle overturn crashes. Most (78.7%) motorcycle overturns occurred within the circulating lanes. Approximately one-third (35.1%) of crashes in the circulating lanes were caused by attempts to avoid a noncontact vehicle. Another 29.7% of crashes were the result of the road conditions (e.g., loose gravel and oil patch). The remaining motorcycle overturn crashes within the circulating lanes were alcohol related or speed related, or resulted from the inexperience of the motorcyclists. None of the motorcycle overturn crashes within the circulating lanes resulted from weather conditions. Approach-related motorcycle overturns involved causal factors different from those associated with circulating overturn crashes. Seven overturn crashes (14.9%) occurred at a roundabout approach. Four of these seven crashes were due to the weather, two crashes were due to alcohol, and only one crash was due to the avoidance of a noncontact vehicle. Only 6.4% of motorcycle overturn crashes occurred at the exit lanes of the roundabout; these crashes were due to weather and road conditions.

Summary of Single-Vehicle Crash Types with Crash Causes

Separate examinations of the run-off-road crashes and overturn crashes revealed the trends that each single-vehicle crash type exhibited. Most (55.3%) run-off-road single-vehicle crashes occurred at the roundabout approach. The primary causes of run-off-road crashes were weather and impaired driving. Most (81.8%) overturn crashes occurred within circulating lanes. The crash causes for overturn crashes varied, but crashes due to road conditions and efforts to avoid a noncontact vehicle were prevalent. A breakdown of single-vehicle crash types and the primary crash causes for each area of the roundabout are shown in Figure 4. Some crashes might have resulted from one crash cause, while others might have been the result of all causes combined.

Age Comparison of Single-Vehicle-Related Crashes

The age of each driver involved in a single-vehicle crash was determined, when possible. Of the 431 crashes, 49 were hit-and-run crashes in which driver age could not be determined. Each crash was classified into an age group on the basis of U.S. Census age group classifications. For each age group, a comparison was done between the proportions of drivers involved in single-vehicle crashes and the total proportion of licensed drivers in Wisconsin, collected from Wisconsin Crash Facts (*28*). To statistically quantify the age group comparison, a two-tailed z-test for proportions was conducted with a 95% level of confidence

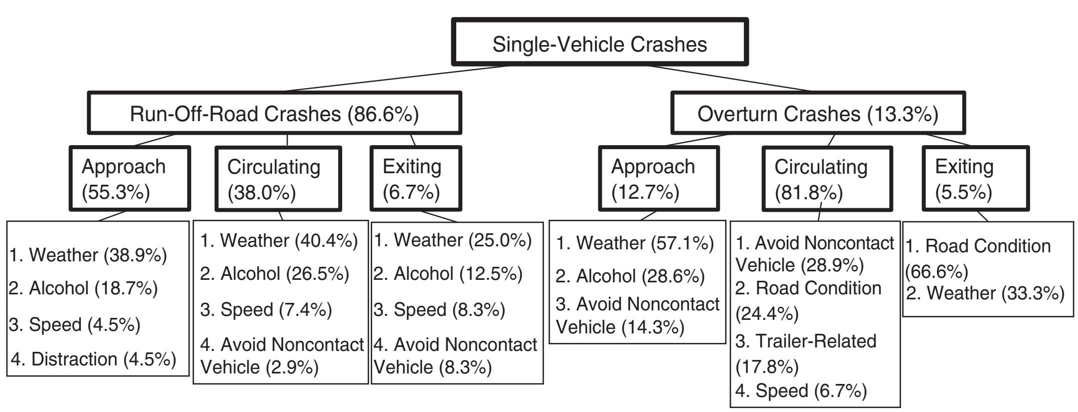


FIGURE 4 Crash causes by single-vehicle crash type and location.

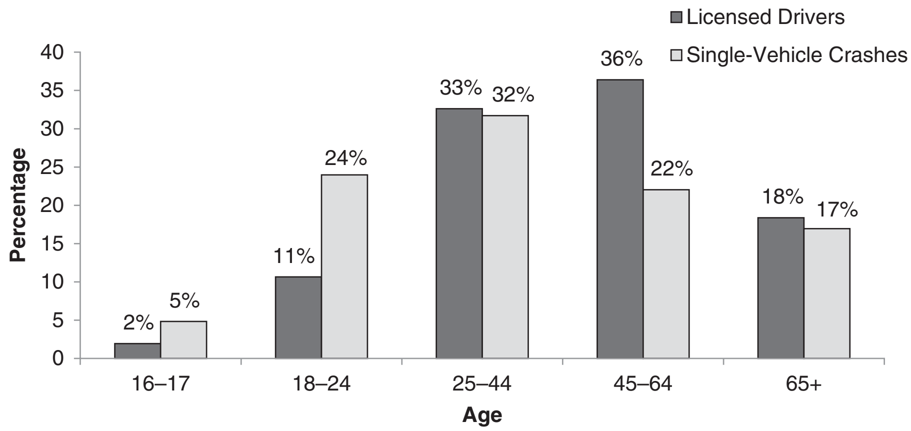


FIGURE 5 Comparison of licensed drivers and single-vehicle crashes in Wisconsin.

(Equation 1). The age group comparison, along with significant results denoted, is shown in Figure 5.

$$z = \frac{p_2 - p_1}{\sqrt{p * (1-p) * \left(\frac{1}{n_1} + \frac{1}{n_2}\right)}} \quad (1)$$

where

p_1, p_2 = proportion of the single-vehicle crashes and licensed drivers, respectively;
n_1, n_2 = numbers of single-vehicle crashes and licensed drivers, respectively; and
p = pooled proportion, which is calculated with Equation 2.

$$p = \frac{n_1 p_1 + n_2 p_2}{n_1 + n_2} \quad (2)$$

Age groups with drivers under 25 were involved in a higher proportion of single-vehicle crashes. Drivers 18 to 24 years of age, who made up 11% of all licensed drivers, were involved in 24% of all roundabout-related single-vehicle crashes, a significantly higher proportion of single-vehicle crashes. In all other age groups, a lower proportion of drivers was involved in single-vehicle crashes. Drivers 45 to 64 years of age were the only other age group found to have significantly different proportions of drivers involved in single-vehicle crashes than total licensed drivers: they accounted for 36% of the licensed drivers in Wisconsin but were involved in only 22% of the single-vehicle crashes. The significantly higher proportion of younger drivers involved in single-vehicle crashes at roundabouts might have resulted from a lack of risk avoidance, aggressive behavior, and distraction, which other age groups did not exhibit, particularly middle-aged drivers (i.e., 45 to 64 years of age). Two single-vehicle crashes involved drivers under 16, which were excluded from the analysis.

The results showed that younger drivers had a propensity to drive more recklessly and at higher speeds than drivers in other age groups. Younger drivers (i.e., 24 years of age and younger) were responsible for 29% of all single-vehicle crashes, and 23% of all injury crashes. Younger drivers were involved in 35% of all weather-related crashes, and nearly two-thirds (61.9%) of speed-related crashes at roundabouts. Younger drivers were involved in 30.3% of all single-vehicle crashes that involved impaired driving at roundabouts, an alarming number, given that the maximum age in this group was only 3 years above the legal drinking age in the United States.

CRASH ESTIMATION MODEL

To construct a model as accurate and specific as possible, only approach-related run-off-road crashes were modeled. They included run-off-road crashes that occurred at the approach (196 crashes) or run-off-road crashes that involved a vehicle collision with the central island directly from an approach (31 crashes) for a total of 227 run-off-road crashes. For this analysis, crashes that resulted from attempts to avoid a noncontact vehicle were excluded because these crashes were similar to entering–circulating and exiting–circulating crash types. At the 53 study roundabouts, 37 roundabouts had four approaches, and 18 had three approaches, for a total of 202 approaches.

Geometric Characteristics of Roundabouts

The geometric characteristic data for the 53 roundabouts used in this study were collected for a 2015 Wisconsin roundabout study (*29*). Approach-specific and general roundabout characteristics were collected for the 53 roundabouts. In total, 13 approach-specific geometric characteristics, as well as seven general roundabout characteristics, were added as potential contributing factors. Of the 13 approach-specific attributes studied, three were continuous variables, and 10 were categorical (Tables 1 to 3). Of the general roundabout attributes, three were continuous, and four were categorical (Table 2). In each table, the ranges of values for continuous variables are shown. For categorical variables, the frequency of each predictor attribute is shown. All categorical variables were two levels, with most in the presence or absence of a feature at the roundabout. Geometric attributes were determined through aerial photographs of the roundabouts. Traffic volume data were obtained from the Wisconsin Department of Transportation (*30*). For this research, traffic volumes were assumed to remain constant during the 6-year analysis period, because average annual daily traffic (AADT) data were not collected every year. This assumption may have been a possible source of error in the model. Approach-specific continuous variables included flare length, entry width, and deflection angle. Posted speed was

TABLE 1 Approach-Specific Characteristics

Attribute	Type	Range of Values
Deflection angle (°)	Continuous	5–54
Entry width (ft)	Continuous	9–22
Flare length (ft)	Continuous	0–275
Posted speed	Categorical	<45 mph–110 (54.5%) ≥45 mph–92 (45.6%)
Number of approach lanes	Categorical	1–113 (55.9%) 2+–89 (44.1%)
Presence of Yield pavement markings	Categorical	Yes–85 (42.1%) No–117 (57.9%)
Presence of pedestrian crossing	Categorical	Yes–70 (34.7%) No–132 (65.3%)
Roundabout in corridor	Categorical	Yes–19 (9.4%) No–183 (90.6%)
Yield sign on left side of approach	Categorical	Yes–182 (90.1%) No–20 (9.9%)
Continuous right turn lane	Categorical	Yes–19 (9.4%) No–183 (90.6%)
Sawtooth or shark teeth pavement markings	Categorical	Yes–10 (5.0%) No–192 (95%)
Approach lane is highway ramp	Categorical	Yes–16 (4.0%) No–194 (96.0%)
Horizontal curve within 250 feet of roundabout	Categorical	Yes–23 (11.4%) No–179 (88.6%)

TABLE 2 General Roundabout Characteristics

Attribute	Type	Range
Approach AADT (vpd)	Continuous	1,000–50,000
Central island radius (ft)	Continuous	29–66
Inscribed circle diameter (ft)	Continuous	92–254
Urban or rural	Categorical	Urban–139 (68.8%) Rural–63 (31.2%)
Number of circulating lanes	Categorical	1–116 (57.4%) 2–86 (42.6%)
Number of approaches	Categorical	3–54 (26.7%) 4–148 (73.3%)
Central island landscaping	Categorical	Yes–161 (79.7%) No–41 (20.3%)

NOTE: vpd = vehicles per day.

modeled as a categorical variable: approach speeds below 45 mph, at 45 mph, or higher. Given that most roundabouts had either one or two approach lanes, the number of approach lanes was condensed, either to one approach lane or two or more approach lanes. Other factors considered included the presence of a horizontal curve within 250 ft of the roundabout—whether the roundabout was in a roundabout corridor or was ramp related—and various pavement markings at the roundabout approaches.

TABLE 3 Approach-Related Run-Off-Road Crash Prediction Model

	Model Coefficient Estimates (*p*-values)			
	(Full Model)	(Interim Modeling Steps)		(Final Model)
Predictor	3-1	3-2	3-3	3-4
Approach specific				
Deflection angle	−.005 (.764)			
Entry width	.018 (.732)			
Flare length	.000 (.899)			
Posted speed	.708 (.016)	1.009 (<.001)	1.048 (<.001)	1.033 (<.001)
Number of approach lanes	.113 (.805)			
Yield pavement markings	−.015 (.960)			
Pedestrian crossing	−.298 (.322)			
Roundabout in corridor	.118 (.786)			
Yield sign left of approach	.658 (.290)			
Continuous right turn lane	.243 (.582)			
Sawtooth pavement markings	−1.318 (.061)	−1.137 (.077)	−.936 (.131)	
Approach is highway ramp	.063 (.910)			
Horizontal curve within 250 ft	−.030 (.936)			
General roundabout				
Approach AADT (vpd)	.382 (.048)	.374 (.015)	.379 (.014)	.375 (.015)
Central island radius (ft)	.016 (.601)			
Inscribed circle diameter (ft)	−.002 (.915)			
Urban or rural	−.061 (.829)			
Number of circulating lanes	−.457 (.277)			
Number of approaches	−.458 (.192)	.368 (.137)		
Central island landscaping	−1.111 (<.001)	−.951 (<.001)	−1.040 (<.001)	−1.081 (<.001)
Model intercept	−5.455 (.023)	−4.192 (.005)	−3.939 (.008)	−3.018 (.026)
Goodness-of-fit metrics				
Log likelihood	−259.369	−262.697	−263.806	−265.051
BIC	629.579	557.062	554.003	551.215
χ^2 likelihood	62.892 (df = 20) $p < .001$	56.238 (df = 5) $p < .001$	54.019 (df = 4) $p < .001$	51.528 (df = 3) $p < .001$

NOTE: df = degrees of freedom.

AADT volumes for each approach were collected. For modeling purposes, the log of the AADT was used. In addition, geometric information (e.g., radii of the inscribed circle diameter and the central island, number of lanes, and number of approaches) was added. Whether the roundabout was urban or rural area was added because driver behavior might have differed depending on the location. Finally, central island landscaping was added because research in Maryland has indicated that landscaped central islands could reduce crashes by increasing the conspicuity of roundabouts (*23*). Although subjective, in the present research landscaping was defined as any built-up structure that obscured, or mostly obscured, the traffic on the other side of the roundabout. Roundabouts with grass and those with little vegetation that blocked an approaching driver's view of the opposite side of the roundabout were not considered landscaped. The purpose of landscaping the central island is twofold: (*a*) to increase conspicuity of the roundabout and (*b*) to create visual blockage.

Negative Binomial Model

Approach-related run-off-road crashes were modeled as the response variable, while the geometric attributes listed in Table 2, *a* and *b*, were modeled as potential predictor variables. Because crash data are rare nonnegative integer count events, the negative binomial model with a log link was used to predict the approach-related run-off-road crashes. The general form of the negative binomial model is shown in Equation 3, and the variance is shown in Equation 4.

$$\log(\mu) = \alpha + \sum_{i=1}^{I} \beta_i x_i \quad (3)$$

$$\text{var} = \mu + D\mu^2 \quad (4)$$

where

μ = expected number of crashes,
α = model intercept,
x_i = ith predictor variable,
β_i = coefficient for each of the x_i significant predictor variables, and
D = overdispersion parameter.

To eliminate insignificant predictor variables and reduce the size of the model, backward stepwise regression was used. For backward stepwise regression, the Bayesian information criterion (BIC) was used as a goodness-of-fit metric to eliminate variables. Use of the BIC is a way to optimize a regression equation for the best fit and to avoid overfitting by adding a penalty for each predictor variable added. In general the lower the BIC, the better the fit of the model. How to calculate the BIC is shown in Equation 5.

$$\text{BIC} = -2 * \ln\left(\hat{L}\right) + k * \ln(n) \quad (5)$$

where

$\hat{L}$ = maximum likelihood,
n = sample size, and
k = number of parameters estimated by the model (including the intercept).

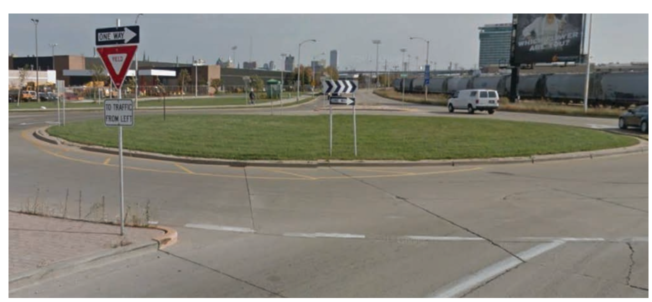
All predictors were originally added to the model. One predictor variable was removed at a time to result in the largest decrease in the BIC. The process of removing a predictor variable was repeated until there was no longer a reduction in BIC, producing a local minimum. Once the BIC was minimized, the final model was produced. The approach-related run-off-road crash estimation model is shown in Table 2. The full model, including all potential predictors, is shown in Column 2-1. Columns 2-2 and 2-3 show the final two steps of the backward stepwise regression. The final model is shown in Column 2-4. The goodness-of-fit metrics log likelihood, the BIC, and the χ^2 likelihood also are shown for each modeling step in Table 2.

The final model had an overdispersion parameter, *D*, of 1.027. The final negative binomial model, along with the significant coefficients, can be seen in Equation 6.

$$\mu = 0.049\text{appAADT}^{0.375} e^{1.033*\text{speed}} e^{-1.081*\text{cntrisllandscaping}} \quad (6)$$

The final model had three significant variables to estimate run-off-road crashes at roundabout approaches. The geometric characteristics approach AADT (appAADT in Equation 6) and the posted speed (speed in Equation 6) were positive, which suggested that, as speed limits increased and AADT increased, run-off-road crashes at approaches also would increase. The posted speed result agreed with previous research that showed speed to be a major factor in run-off-road crashes (*19, 22, 23, 25*). The approach AADT result was intuitive: as traffic volume increased, traffic crashes increased as well. Finally, central island landscaping (cntrisllandscaping in Equation 6) was significant. When a roundabout had central island landscaping, run-off-road crashes were expected to decrease, which agreed with previous research from Maryland that suggested the increase in conspicuity could reduce crashes (*23*). Figure 6*a* shows a roundabout with a central island that is landscaped. Figure 6*b* shows a central island that is not landscaped.

(a)



(b)

FIGURE 6 Comparison of central islands: (*a*) with landscaping and (*b*) without landscaping.

CONCLUSIONS

Roundabouts are a proven countermeasure to improve intersection safety, particularly with respect to fatal and injury crashes. Roundabout design reduces the occurrence of crash types (e.g., angle, head-on, left-turn related collisions). However, roundabouts have been shown to increase crash types such as single-vehicle collisions. To understand the design considerations that affect single-vehicle crashes at roundabouts can further improve the safety benefits of roundabouts. Fifty-three roundabouts were examined in this study, at which 431 single-vehicle crashes occurred across 6 years. The crash causes, the location and types of single-vehicle crashes, and the ages of drivers involved in single-vehicle crashes were examined. Finally, a model with geometric characteristics was constructed to estimate single-vehicle run-off-road crashes at approaches.

One-third of single-vehicle crashes were weather related, followed by impaired driving as the cause. Together weather and impaired driving accounted for more than half of single-vehicle crashes. Weather-related crashes resulted in less severe crashes, whereas road conditions (e.g., loose gravel) and crashes as a result of efforts to avoid a noncontact vehicle were associated with a higher proportion of injuries than total single-vehicle crashes. These crash causes primarily involved a motorcycle that overturned as a result of a crash.

Two types of single-vehicle crashes occurred: overturns and run-off-road crashes. Run-off-road crashes were most frequent, accounting for more than 86% of single-vehicle crashes. Most of the run-off-road crashes occurred at roundabout approaches. The primary causes for run-off-road crashes were weather and impaired driving. Overturn crashes primarily occurred within the circulating lanes. Overturn crashes resulted primarily from road conditions and from efforts to avoid a noncontact vehicle. In addition, several crashes within the circulating lanes involved trailers that had overturned.

Younger drivers (18 to 24 years of age) were found to be involved in a significantly higher proportion of single-vehicle crashes than licensed drivers in that age group. Younger drivers made up nearly a third of all single-vehicle crashes as a result of impaired driving. In addition, younger drivers were responsible for nearly two-thirds of speed-related single-vehicle crashes. These results showed issues common among younger drivers and suggested that younger drivers might need further training and exposure to roundabouts to understand how to navigate them safely. Drivers more than 24 years of age were involved in a lower proportion of single-vehicle crashes than the proportion of licensed drivers for that age group. Middle-aged drivers (45 to 64 years of age) were involved in a significantly lower proportion of single-vehicle crashes.

Finally, a model was constructed to estimate approach-related, single-vehicle, run-off-road collisions. The model included 227 run-off-road collisions, and 20 potential factors with an effect on run-off-road crashes. Three factors were found to significantly influence approach-related run-off-road collisions: approach AADT, posted speed, and whether the central island was landscaped. As approach AADT and posted speed increased, the expected number of run-off-road crashes at an approach increased. When a central island was landscaped, approach-related run-off-road crashes decreased as a result of the increased conspicuity. The model created could serve as a way to estimate run-off-road crashes at roundabout approaches.

The results showed clear single-vehicle crash trends. Weather and speed were large factors that influenced the frequency of single-vehicle crashes. Younger drivers were responsible for a large portion of single-vehicle crashes and were at particular risk when impaired and with respect to speeding. High-speed approaches were found to be less safe, and landscaped central islands improved safety at the roundabouts. In general, an increase in conspicuity helped drivers to become aware that they were approaching a roundabout, which may have led them to proceed with caution and to reduce their speeds appropriately.

Although this research is helpful to understand trends in single-vehicle crashes, more work needs to be done to fully understand single-vehicle crashes at roundabouts. Future work will include the development of a comprehensive single-vehicle crash model, as well as an examination of all approach-related crashes and circulating crashes. Landscaped central islands need further investigation as a crash countermeasure. In addition, because impaired driving was responsible for a high frequency of single-vehicle crashes at roundabouts, further examination of alcohol-related crashes at roundabouts might help mitigate that safety concern.

REFERENCES

1. Rodegerdts, L. A. *Status of Roundabouts in North America.* Presented at 4th International Roundabout Conference, Seattle, Wash., 2014. http://teachamerica.com/RAB14/RAB14posters/RAB14P_Rodegerdts.pdf. Accessed July 3, 2016.
2. Russell, E., S. Mandavilli, and M. J. Rys. *Operational Performance of Kansas Roundabouts: Phase II.* Final report. KSU-01-04. Kansas Department of Transportation, Topeka, 2005.
3. Uddin, W. *Performance Evaluation of Roundabouts for Traffic Delay and Crash Reductions in Oxford, MS.* State Study 213. Final report. Publication FHWA-MS-DOT-RD-11-213. Mississippi Department of Transportation, Jackson, 2011.
4. Persaud, B. N., R. A. Retting, P. E. Garder, and D. Lord. Safety Effect of Roundabout Conversions in the United States: Empirical Bayes Observational Before–After Study. *Transportation Research Record: Journal of the Transportation Research Board,* No. 1751, 2001, pp. 1–8. http://dx.doi.org/10.3141/1751-01.
5. Elvik, R. Effects on Road Safety of Converting Intersections to Roundabouts: Review of Evidence from Non-U.S. Studies. *Transportation Research Record: Journal of the Transportation Research Board,* No. 1847, 2003, pp. 1–9. http://dx.doi.org/10.3141/1847-01.
6. FHWA. *Roundabouts: A Safer Choice.* Publication FHWA-SA-08-006. U.S. Department of Transportation, 2008.
7. Rodegerdts, L., J. Bansen, C. Tiesler, J. Knudsen, E. Myers, M. Johnson, M. Moule, B. Persaud, C. Lyon, S. Hallmark, H. Isebrands, R. B. Crown, B. Guichet, and A. O'Brien. *NCHRP Report 672: Roundabouts: An Informational Guide,* 2nd ed., Transportation Research Board of the National Academies, Washington, D.C., 2010.
8. Khan, G., A. Bill, D. Chiu, and D. Noyce. *Safety Evaluation of Wisconsin Roundabouts: Phase 2.* Wisconsin Department of Transportation, Madison, 2013.
9. Bill, A., X. Qin, M. Chitturi, and D. A. Noyce. *Comprehensive Evaluation of Wisconsin Roundabouts, Volume 2: Safety Findings.* Wisconsin Department of Transportation, Madison, 2011.
10. Zheng, D., X. Qin, R. Tillman, and D. A. Noyce. Measuring Modern Roundabout Traffic Conflict Exposure. *Journal of Transportation Safety and Security,* Vol. 5, No. 3, 2013, pp. 208–223. http://dx.doi.org/10.1080/19439962.2012.720003.
11. FHWA. *Intersection Safety.* U.S. Department of Transportation, 2014. https://www.fhwa.dot.gov/research/topics/safety/intersections/. Accessed July 15, 2016.
12. FHWA. Nine Proven Crash Countermeasures. *Safety Compass,* Vol. 3, No. 2, U.S. Department of Transportation, 2009.
13. Robinson, B. W., L. Rodegerdts, W. Scarborough, W. Kittelson, R. Troutbeck, W. Brilon, L. Bondzio, K. Courage, M. Kyte, J. Mason, A. Flannery, E. Myers, J. Bunker and G. Jacquemart. *Roundabouts: An Informational Guide.* Publication FWHA-RD-00-067. U.S. Department of Transportation, 2000.
14. Retting, R. A., B. N. Persaud, and P. E. Garder. Crash and Injury Reduction Following Installation of Roundabouts in the United States. *American Journal of Public Health,* Vol. 91, No. 4, 2001, pp. 628–631. http://dx.doi.org/10.2105/AJPH.91.4.628.

15. Eisenman, S., J. Josselyn, G. List, B. Persaud, C. Lyon, B. Robinson, and R. Troutbeck. *Operational and Safety Performance of Modern Roundabouts and Other Intersection Types.* Publication NYSDOT C-01-47. New York State Department of Transportation, Albany, 2005.
16. Hydén, C., and A. Várhelyi. The Effects on Safety, Time Consumption and Environment of Large Scale Use of Roundabouts in an Urban Area: A Case Study. *Accident Analysis and Prevention,* Vol. 32, No. 1, 2000, pp. 11–23. http://dx.doi.org/10.1016/S0001-4575(99)00044-5.
17. De Brabander, B., E. Nuyts, and L. Vereeck. Road Safety Effects of Roundabouts in Flanders. *Journal of Safety Research,* Vol. 36, No. 3, 2005, pp. 289–296. http://dx.doi.org/10.1016/j.jsr.2005.05.001.
18. Rodegerdts, L., M. Blogg, E. Wemple, E. Myers, M. Kyte, M. Dixon, G. List, A. Flannery, R. Troutbeck, E. Brilon, N. Wu, B. Persaud, C. Lyon, D. Harkey, and D. Carter. *NCHRP Report 572: Roundabouts in the United States,* Transportation Research Board of the National Academies, Washington, D.C., 2007.
19. Isebrands, H. Crash Analysis of Roundabouts at High-Speed Rural Intersections. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2096, 2009, pp. 1–7. http://dx.doi.org/10.3141/2096-01.
20. NHTSA. *Traffic Safety Facts 2014.* Publication DOT HS 812 261. U.S. Department of Transportation, 2015.
21. Liu, C., and R. Subramanian. *Factors Related to Fatal Single-Vehicle Run-Off-Road Crashes.* Publication DOT HS 811 232. NHSTA, U.S. Department of Transportation, 2009.
22. Eustace, D., O. Almutairi, P. W. Hovey, and G. Shoup. Using Decision Tree Modeling to Analyze Factors Contributing to Injury and Fatality of Run-Off-Road Crashes in Ohio. Presented at 93rd Annual Meeting of the Transportation Research Board, Washington, D.C., 2014.
23. Mandavilli, S., A. T. McCartt, and R. A. Retting. Crash Patterns and Potential Engineering Countermeasures at Maryland Roundabouts. *Traffic Injury Prevention,* Vol. 10, No. 1, 2009, pp. 44–50. http://dx.doi.org/10.1080/15389580802485938.
24. Highway Loss Data Institute. *Roundabouts.* Insurance Institute for Highway Safety. http://www.iihs.org/iihs/topics/t/roundabouts/qanda. Accessed June 20, 2016.
25. Steyn, H. J. *Safety: Fatal and Injury Crash Evaluation in the U.S.* Presented at 4th International Roundabout Conference, Seattle, Wash., 2014. http://teachamerica.com/RAB14/RAB1406CSteyn/index.htm. Accessed July 1, 2016.
26. *Facilities Development Manual.* Wisconsin Department of Transportation, Madison, 2016, pp. 72–73.
27. University of Wisconsin Madison Traffic Operations and Safety Laboratory. *The WisTransPortal Project.* http://transportal.cee.wisc.edu. Accessed June 24, 2016.
28. *Wisconsin Crash Facts: III. Driver Data.* Wisconsin Department of Transportation, Madison, 2013. http://wisconsindot.gov/Documents/safety/education/crash-data/2013/section3.pdf. Accessed July 22, 2016.
29. Burdett, B., I. Alsghan, L. Chiu, A. R. Bill, and D. A. Noyce. Analysis of Rear-End Crashes at Roundabout Approaches. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2585, 2016, pp. 29–38. http://dx.doi.org/10.3141/2585-04.
30. Wisconsin Department of Transportation. *Historical Traffic Counts by County.* http://www.dot.wisconsin.gov/travel/counts/maps.htm. Accessed June 24, 2016.

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