Appendix P
Analysis for Roundabout Entrance & Exit Geometry

P.1 WHITE PAPER; ROUNDABOUT ENTRANCE AND EXIT GEOMETRY

Entrance and exit geometries play an important role in controlling speed and movement of a vehicle through a roundabout. In general, providing roundabout alignments that increase flow at the exit may provide increased gaps in the circulating traffic stream and may provide greater opportunities for entering vehicles. Currently, there is significant discussion between roundabout designers about the best method to determine exit geometry and to control exit speed within design parameters. The discussion centers around the prediction of vehicle speed and how to calculate appropriate values for design. The standard method has been to utilize the speed, radius relationship as shown in Figure P-1. The graph was derived using the basic equation for velocity and minimum radius from the AASHTO document A Policy on Geometric Design of Highways and Streets; $V=\sqrt{15R(e+f)}$, where superelevation, e, is held to +2% and -2% with side friction factor, f, values assumed for general design.

Figure P-1: Estimated Vehicle Speed and Radius Relationship

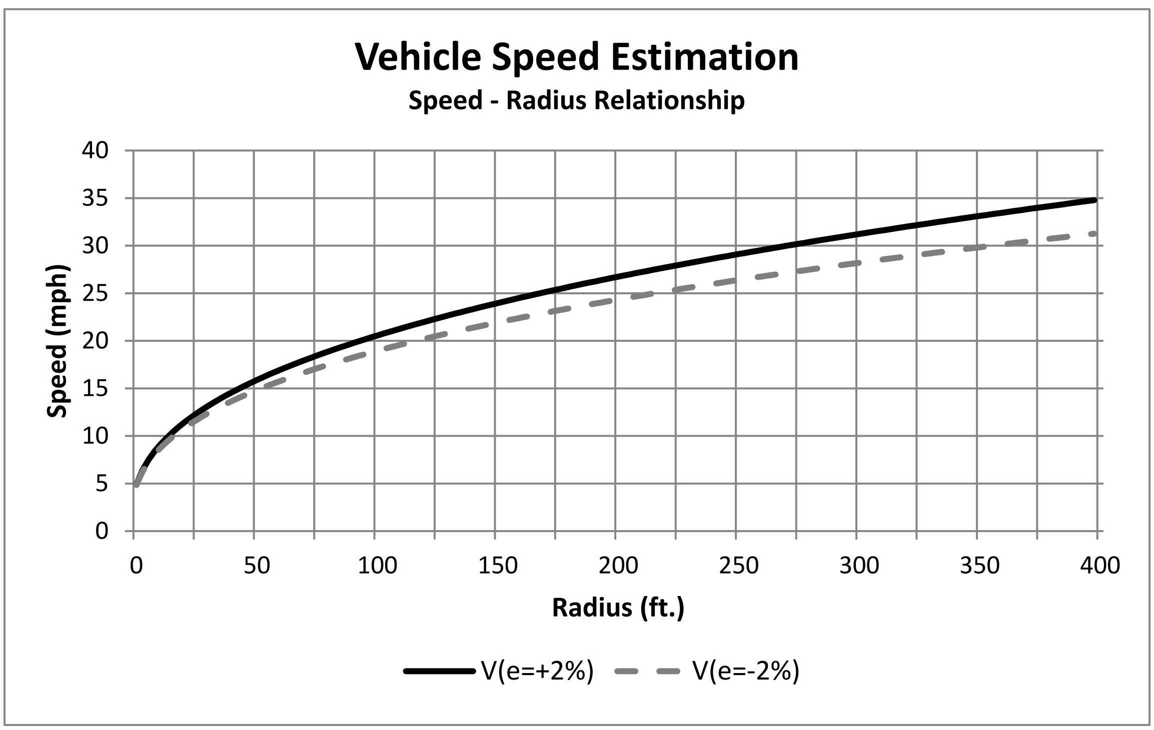


Table P–1 is a tabular form of the values in Figure P-1 reported at 25 ft. radius intervals. In addition, NCHRP Report 672 Roundabouts: An Informational Guide, provides simplified equations to calculate speeds for given radii as well. Equation 1 is for +2% superelevation and Equation 2 is for -2% superelevation.

Table P–1: Speed, Radius Relationship

Radius (ft.)	V(+2%) (mph)	V(-2%) (mph)
25	12	11
50	16	15
75	18	17
100	20	19
125	22	20
150	24	22
175	25	23
200	27	24
225	28	25
250	29	26
275	30	27
300	31	28
325	32	29
350	33	30
375	34	31
400	35	31

Speed (V), Radius (R) Relationship Equations

Equation 1:

NCHRP Report 672

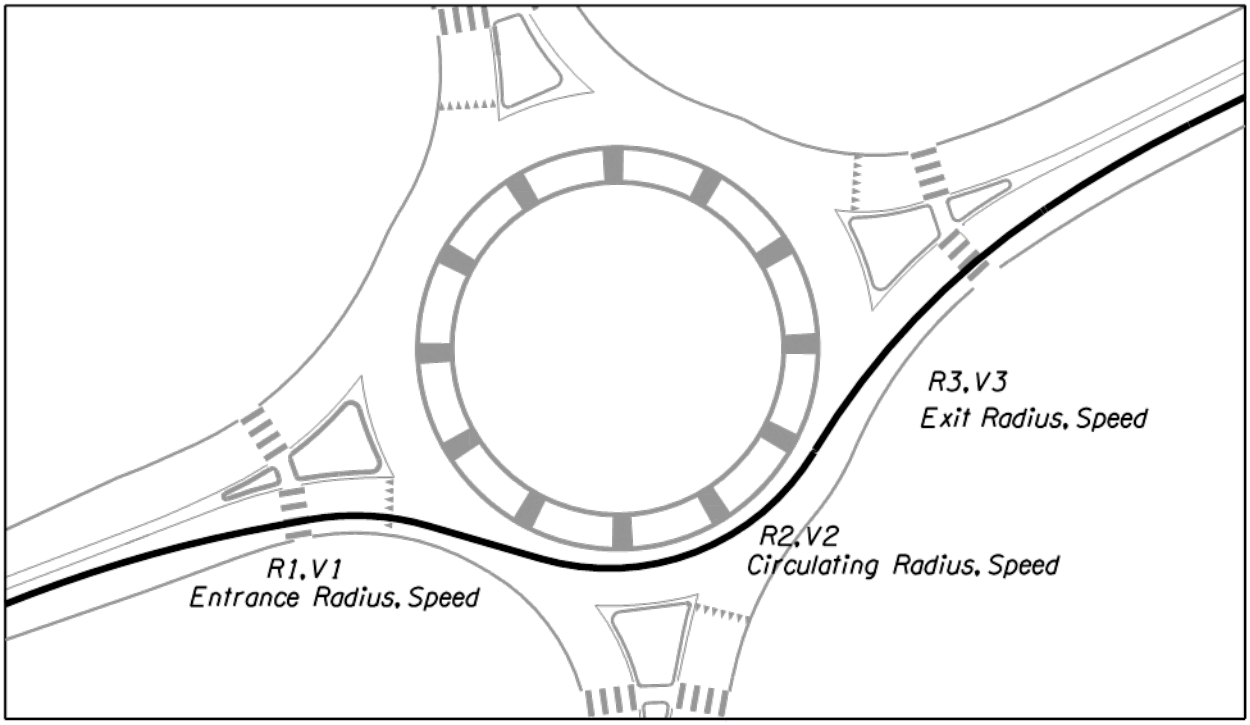
$V=3.4415R^{0.3861}$; e= 2%

Equation 2:

NCHRP Report 672

$V=3.4614R^{0.3673}$; e= -2%

Figure P-2: Vehicle Path Through a Roundabout - Speed, Radius



For superelevation other than +/- 2%, Equation 3, AASHTO Minimum Radius needs to be used with an appropriate side friction factor, f.

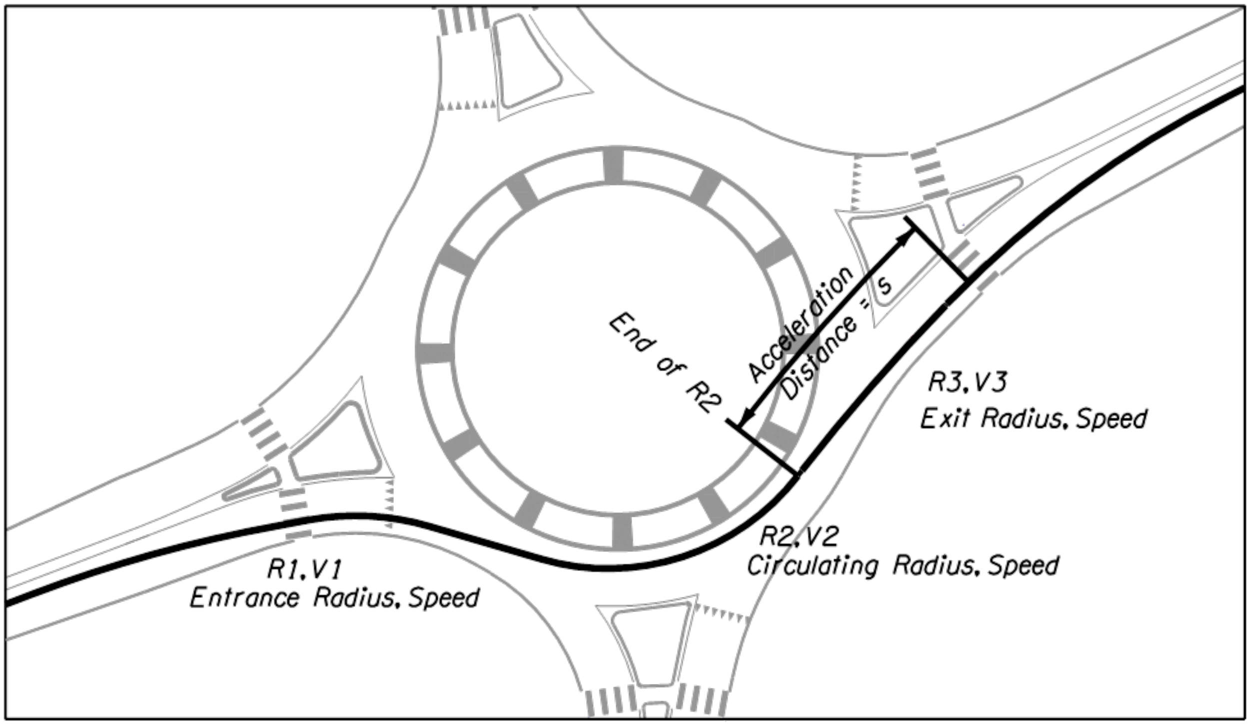
However, there is thought that exit radii designed too small to reduce predicted exit speed in an attempt to focus on pedestrian safety may unnecessarily limit overall roundabout capacity. This leads to the question, then, how to calculate appropriate exit radii to maximize capacity and still protect pedestrian movements at the downstream crosswalk?

P.1.1 Research for Alternate Calculation Method

Alternate Design Methods for Pedestrian Safety at Roundabout Entries and Exits: Crash Studies and Design Practices in Australia, France, Great Britain and the USA Bill Baranowski, Edmund Waddell (2004)

Research done in 2004 by Bill Baranowski of Roundabouts USA and Edmund Waddell of Michigan DOT investigated entrance and exit geometry in order to determine appropriate roundabout alignments to increase capacity without negatively effecting pedestrian safety. The investigation determined that R_1 and R_2 values along with vehicle acceleration from R_2 through R_3 may play more of a role in exit speed than exit radius, R_3, alone. The researchers looked at the circulation radius, speed; R_2,V_2 relationship, the distance from the end of the R_2 radius to the exit crosswalk and the potential acceleration of a vehicle over that distance.

Figure P-3: : Vehicle Path Through a Roundabout Speed, Radius, Acceleration Distance



The research assumed an exiting vehicle is capable of accelerating along a given R_3 radial path with an acceleration rate of 3.5 ft/s^2 and also assumed acceleration starts at the end point of R_2. The standard Newtonian equation for uniform acceleration was used to compute potential vehicle speeds at the exit crosswalk.

Newtonian Equation for Speed and Acceleration

$$V_f^2 = V_i^2 + 2aS$$

Where: V_f = Final R_3 Speed, ft/s (V_3, Exit Speed)

V_i = Initial R_2 Speed (V_2, Circulating Speed)

a = Acceleration, (3.5 ft/s^2)

S = Distance, ft (End of R_2 to Crosswalk)

After analyzing theoretical roundabout layouts and investigating several existing roundabouts, the researchers concluded that the R_2,V_2 radius, speed relationship and vehicle acceleration from R_2 to the crosswalk as a vehicle exits a roundabout has more effect on the vehicle speed at the exit crosswalk than a tighter exit radius using only the radius, speed relationship for R_3 alone. The theory then is that exit geometry (radius) can be relaxed to increase overall capacity and not appreciably affect pedestrian activity or safety at the exit crosswalk by increased vehicle speed. This may prove to be true for small acceleration distance values coupled with relative radius values in order to predict and control maximum potential exit speed. However, effectively controlling this relationship may not always be easily accomplished.

While the theory may have validity, it is only one analysis and appropriate application is critical to its effectiveness for speed prediction and control. Two key variables in the calculation are the distance available to accelerate prior to the exit crosswalk and the acceleration rate itself. If available acceleration distance is kept short, the exit speed may not be greatly affected. However, in larger diameter roundabouts, the available distance to accelerate may have an appreciable effect on exit speed. This may be particularly true for multi-lane roundabouts. The acceleration rate chosen for design will also have an effect on the predicted speed. The research used a rate of 3.5 ft/sec^2 for exit speed calculations. This is not a particularly fast rate of acceleration and may be acceptable for a curvilinear acceleration rate for small to moderate radii transitioning to the exit. However, some roundabout designs are utilizing large exit radii that become almost tangential. In these designs, it would be expected that vehicles would be accelerating from R_2 to the exit at a rate greater than 3.5 ft/sec^2. NCHRP Report 672, Roundabouts: An Informational Guide uses 6.9 ft/sec^2 for an acceleration rate in similar equations. This is nearly twice the rate used in the Baranouski/Waddell research and may be a better estimation when considering that the current vehicle fleet is capable of maximum performance, straight line acceleration rates of 9 ft/sec^2 for a four cylinder compact car to over 20 ft/sec^2 for a high performance eight cylinder vehicle with the average for all vehicles about 13 ft/sec^2. (See Table P–2: Maximum Straight Line Acceleration Performance by Vehicle)

The Baranowski/Waddell research is significant in that it shows the role R_2 can play in controlling exit speed when alignments incorporate smaller curvilinear radii and short acceleration distances between R_2 and the exit crosswalk. However, for larger radius or tangential exits, the acceleration rate for predicted speed calculations may need to be increased to better represent conditions as available acceleration distances increase.

P.1.2 NCHRP Report 572, Roundabouts in the United States

Rodegerdts, Blogg, Wemple, Myers, et al (2007)

NCHRP Report 572 was a research project that investigated roundabouts in the United States and analyzed their operation. Authors of NCHRP Report 572 collected data from 103 roundabouts from around the United States. One of their findings indicated that observed entry and exit speeds did not always correlate well to the predicted entry and exit speeds determined for a given roundabout using the speed, radius relationship. The predicted speeds tended to be greater than the observed speeds. This was particularly evident for roundabouts with tangential or large entrance or exit radii. However, the speed, radius relationship did well in predicting observed circulating speeds through the R_2 and the R_4 pathways around the central island. It is unclear as to why the speed, radius relationship is effective to predict speeds for pathways around the central island radius but is not as effective when predicting speeds in relation to entry and exit radii when correlated to observed speeds at specific roundabouts. From their observations and analysis, the authors developed equations that, in some locations, may better predict entry and exit speeds based on vehicle deceleration and acceleration ability. Like the previous research work done in 2004, these equations include vehicle deceleration and acceleration parameters based on observations and analysis and use the standard equation for uniform acceleration as a basis. These equations are also presented in NCHRP 672, Roundabouts: An Informational Guide, second edition (2010) to calculate predicted values for V_1 and V_3 along a vehicle's fastest path as it enters and exits a roundabout. The guide suggests these equations can be used as an alternative to using values derived from the simplified speed, radius relationships. However, as a cautionary statement, since predicted V_2 values derived from the speed, radius relationship seem to correlate to observed V_2 values, there may be other factors involved like driver behavior, driver expectation, driver familiarity, etc. affecting the correlation of predicted exit speeds and observed exit speeds rather than straight forward correlations to radial path, speed or acceleration.

Equation 4 – Alternative Entrance Speed Calculation, V_1

$$\boldsymbol{V_1 = \frac{1}{1.47}\sqrt{(1.47V_2)^2 + 2a_{1,2}d_{1,2}}}$$

V_1 = entry speed, mph

V_2 = circulating speed based on path radius, mph

$a_{1,2}$ = deceleration between point of interest along v_1 path and mid-point of V_2 path, = -4.2 ft/s^2

$d_{1,2}$ = distance between point of interest along V_1 path and mid-point of V_2 path, ft.

The deceleration rate of -4.2 ft/s^2 for entry speed was developed from the observed driver/vehicle behavior at the researched sites. While this equation had better correlation predicting entry speed with observed speed, the authors also included the following statement in NCHRP 572:

> *"However, given the hesitancy currently exhibited by drivers under capacity conditions, the observed entry speeds may increase over time after drivers acclimate further. Therefore, the research team believes that an analyst should be cautious when using deceleration as a limiting factor when establishing entry speeds for design. Furthermore, the research team believes that a good design should rely more heavily on controlling the entry path radius as the primary method for controlling entry speed, particularly for the fastest combination of entry and circulating path (typically the through movement)."*

NCHRP Report 672, Roundabouts: An Informational Guide, second edition also addresses this concern and states:

> *"Analysts should use caution in using deceleration as a limiting factor to establish entry speed for design. To promote safe design, deflection of the R_1 path radius should be the primary method for controlling entry speed. Therefore, while Equation 6-3 may provide an improved estimate of actual speed achieved at entry, for design purposes it is recommended that predicted speeds from Equation 6-1 be used."*
>
> *(Note: In this White Paper, NCHRP Report 672 Equation 6-3 and Equation 6-1 are reported as Equation 4 and Equation 1 respectively)*

Similar to entry speed, NCHRP Report 572 developed an equation that utilizes vehicle acceleration ability for predicting exit speed based on the standard uniform acceleration equation to better correlate predicted exit speed with observed exit speed for investigative purposes. As with the deceleration rate for entry speed, the report developed a vehicle exit acceleration value of 6.9 ft/s^2 from observed information.

Equation 5 – Alternative Exit Speed Calculation, V_3

$$\boldsymbol{V_3 = \frac{1}{1.47}\sqrt{(1.47V_2)^2 + 2a_{2,3}d_{2,3}}}$$

V_3 = Exit Speed, mph

V_2 = circulating speed based on path radius, mph

$a_{2,3}$ = average acceleration between midpoint of V_2 path and the point of interest along V_3 path = 6.9 ft/s^2

$d_{2,3}$ = distance along vehicle path between midpoint of V_2 path and the point of interest along the V_3 path, ft.

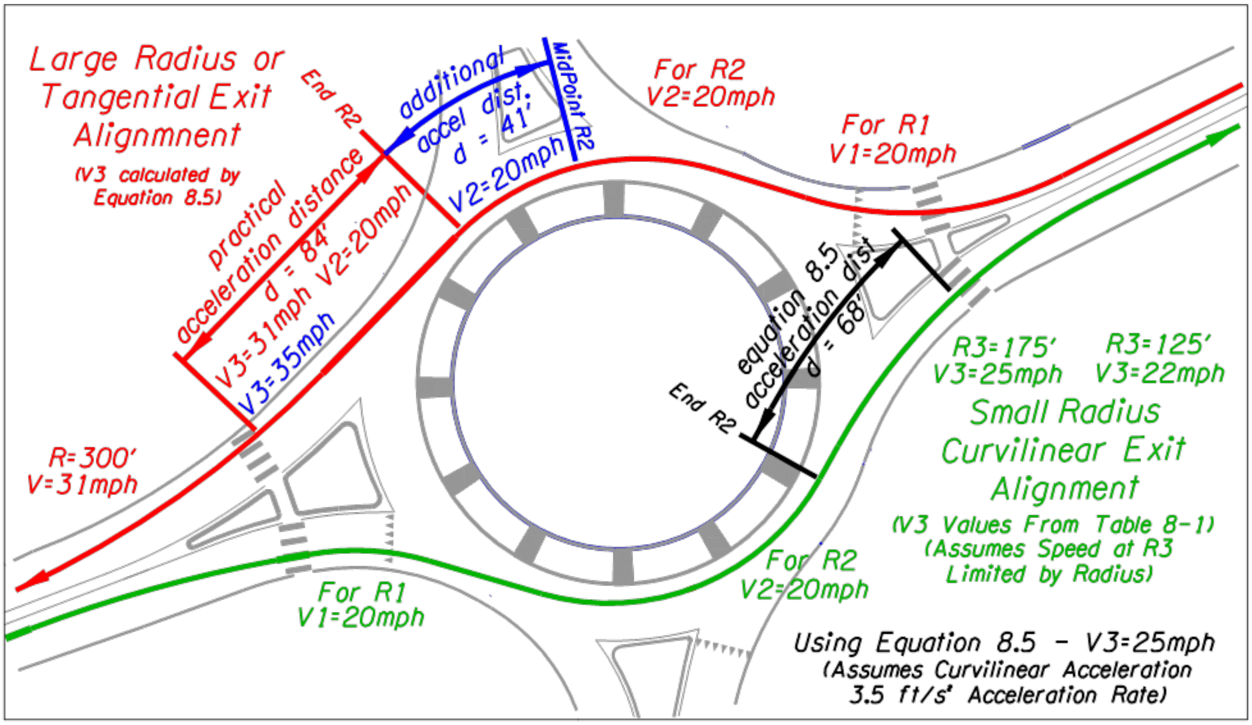
The authors of NCHRP 572 did not provide a caveat for not using the alternate V3 calculation method for design as was provided for the alternate V1 calculation method. There is no explanation provided in the report to indicate why one calculation may be considered more valid than the other. One must remember the reason for the derivation of these equations. The intent was to provide a prediction of exit speed that better correlated to observed exit speed at roundabout locations. The use of these equations lies in the assumption that since the predicted exit speed using the speed, radius relationship is greater than the observed speed, there must be something affecting the speed, radius relationship at exits. Acceleration rates were determined to make a better correlation. However, it works fine for R2,V2 and R4,V4 predicted and observed values. There may be other driver behavior factors that also affect observed R1,V1 and R3,V3 relationships. The authors are concerned this is the case with entrance speed and the same may be true for exit speed. The derived equations use a single deceleration or acceleration rate determined from observed data. Applying these acceleration rates to large radius or tangential exits and small radius, tight curvilinear exits equally may not produce effective design results in both cases. Using the same rates for both exit types assumes acceleration in a straight line or in a large radius is the same as acceleration in a tighter curvilinear path. This may not be the case. Therefore, lowering the acceleration rate for smaller radius paths seems reasonable. The research done in 2004 used 3.5 ft/s2 as an acceleration rate for their investigation into exit geometry. This seems a more reasonable acceleration rate for smaller radial paths. NCHRP 572 uses 6.9 ft/s2 as an acceleration rate. This seems reasonable for larger radius or tangential exits and seems to represent where, by observation, American drivers currently feel comfortable when exiting a roundabout. However, will this rate increase as drivers become more familiar with roundabouts? This is a concern of the authors of NCHRP Report 572 for V1 values.

In addition to determining an acceptable acceleration rate, the other two critical variables in these equations are the V2 speed and the distance, d, over which the deceleration or acceleration can take place. Therefore, if a large radius or tangential exit is designed for a roundabout, the R2 value must provide the appropriate design V2 and the acceleration distance must be effective in limiting a vehicle's potential downstream speed to design values.

Figure P-4 is a hypothetical roundabout layout based on real roundabout dimensions that portrays potential differences in speed between a smaller curvilinear exit and a more tangential exit. The vehicle path alignment shown from lower left to upper right (green) assumes radii for R1 and R2 that provide a 20 mph V1 and V2. The curvilinear R3 exit radius is shown as both 175 ft. and 125 ft. for illustrative purposes and correlates to a V3 speed of 25 mph and 22 mph respectively. These V3 values are based on the speed, radius equations discussed previously in this report and is shown in Table P–1, and Figure P-4. For comparison, the speed, acceleration equation was used to calculate a predicted V3 exit speed along the radial R3 path. Since the exit radius is small, using the 3.5 ft/s2 acceleration rate discussed previously and coupled with the relatively short acceleration distance shown, a predicted V3 of 25 mph was determined. This is equal to the value predicted for V3 using the speed, radius relationship for a 175 ft. exit radius. This is in line with the conclusions of the 2004 research report. However, keep in mind, this geometry has a smaller curvilinear alignment with a short acceleration distance that helps limit a vehicle's ability to accelerate. For comparison, increasing the acceleration rate for the calculation to the NCHRP Report 572 value of 6.9 ft/s2 yields a predicted speed of 29 mph at the crosswalk. This is beginning to reach the unacceptable level for speed at the crosswalk when considering pedestrian safety.

Large radius or tangential exit geometry set for increased capacity or exit geometry opened up due to skewed approach alignments or other site specific parameters that might dictate positioning of roundabout elements may have equal or greater impact to potential vehicle speeds at the crosswalk.

Figure P-4: Exit Geometry - Comparison Tangential and Small Radius



The vehicle path shown on the opposite side of the roundabout from upper right to lower left (red) in Figure P-4 also assumes radii for R1 and R2 that provide a 20 mph V1 and V2. However, the V3 value of 31 mph is based on the potential for vehicle acceleration from the end of R2 to the crosswalk. This distance is shown as a "practical acceleration distance", d, and for this layout is equal to 84 ft. This distance assumes a driver does not accelerate until reaching the end of the circulating path radius R2. This is the approach the researchers in 2004 preferred. However, the equation parameters listed in NCHRP 672, Roundabouts: An Informational Guide, second edition define the acceleration distance as the distance from the midpoint of the V2 path and a point of interest along the V3 path. The point of interest is the downstream crosswalk in this analysis. Adding the additional acceleration distance back along the path to the midpoint of R2 and assuming a vehicle is capable of accelerating at 6.9 ft/s2 along this reversing radial to tangential path, yields a total distance of 124 ft. that a vehicle can accelerate prior to the downstream crosswalk increasing the calculated V3 speed to 35 mph. These calculated speeds are 6 mph and 10 mph faster than the predicted V3 speed of 25 mph at the tighter curvilinear exit on the opposite path of the roundabout. Either of these speeds would be considered excessive for design at the downstream crosswalk. This exemplifies the need to limit the acceleration distance, d, to provide acceptable exit speed if a tangential or large radius design is used.

P.1.3 Conclusion

The two research projects discussed both used uniform acceleration in their calculations. However, they each used different rates of acceleration. Baranowski and Waddell used 3.5 ft/s2 for acceleration. NCHRP Report 573 used 6.9 ft/s2, which is almost double the rate used by Baranowski and Waddell. Both these rates appear to be rates that were field observed by the authors of the reports. The difference may be attributed to the focus of the individual research. Baranowski and Waddell were studying roundabout locations where they considered exit radii to be excessively tight to restrict speeds. Therefore, the observed rates of acceleration were compatible with the geometry. In the case of NCHRP Report 572, the authors were trying to correlate observed exit speed with predicted speed and they noted there was a greater discrepancy when the exit radius was large – predicted speed greater than actual observed speed. In these cases, it appears the acceleration rate was determined to match the observed speed and the 6.9 ft/s2 value they determined in 2007 may in fact be a comfortable rate for American drivers at larger radius exits. This is further borne out when looking at potential 0 – 60 mph maximum performance characteristics of the current vehicle fleet. Table P–2 is a listing of maximum performance and straight line acceleration of various late model production vehicles ranging from 4 cylinder compact cars to high performance 10 cylinder "muscle cars". The data was collected from the on-line automotive sight AutoRooster at http://www.autorooster.com. The site reports 0-60 times for a variety of current vehicles. The corresponding accelerations were calculated and added to the table as 60 mph acceleration values in ft/s2. The acceleration values ranged from 9.09 ft/s2 for a 2008 Honda Civic, 4-cylinder vehicle to 24.50 ft/s2 for a 2010 Dodge Viper, 10-cylinder vehicle. The mathematical average for all the vehicles in the table is 12.89 ft/s2. This indicates that the 6.9 ft/s2 value determined from observed speeds in NCHRP Report 572 may be an acceptable overall value as a "comfortable" acceleration rate to most drivers, since the average in Table P–2 of 12.89 ft/s2 was determined from maximum, straight line performance.

Currently, there is no definitive answer to what is the best method to predict entrance and exit speed when designing a roundabout. Research has shown that in some cases where exit radii are smaller and/or acceleration distances are short limiting a vehicle's ability to accelerate prior to the exit crosswalk, opening up exit geometry may not have a great effect on exit speed. However, relaxed exit geometry that increases acceleration distances and acceleration rates can potentially have significant effects on the exit crosswalk impacting pedestrian movements. This is particularly true for multi-lane roundabouts in off-peak times when a vehicle's fastest path may cross adjacent lanes. In any roundabout layout, it is the designer's responsibility to provide vehicle alignments that consistently control vehicle speeds from entrance to exit in an effective manner for all modes of transportation utilizing the roundabout. For this reason, after the above discussion, it seems reasonable to use roundabout entrance and exit alignments that limit a driver's ability to accelerate prior to the exit crosswalk and it appears that a good method to do that is the standard radius, speed relationship.

Table P–2: Maximum Straight Line Acceleration Performance by Vehicle

Maximum Performance - Straight Line Speed, Acceleration				
Data From AutoRooster (autorooster.com/0-60-times)			60 mph dist. (ft)	60 mph accel. (ft/sec^2)
Vehicle Data	0-60 (sec)	1/4 mile (sec)		
2008 Honda Civic, 4cyl.	9.7	17.1	427.8	9.09
2010-12 Nissan Versa, 4 cyl.	9.4	18.3	414.5	9.38
2013 Ford Escape, 4 cyl.	9.3	17.4	410.1	9.48
2011-14 Chevy Cruze, 4 cyl.	9.0	16.5	396.9	9.80
2009-12 Toyota Corolla. 4 cyl.	8.9	16.7	392.5	9.91
2010-13 Chevy Tahoe, 8 cyl.	8.5	16.9	374.9	10.38
2013 Ford Fusion, 4 cyl.	8.5	16.9	374.9	10.38
2014 Ford Focus, 4 cyl.	8.5	16.7	374.9	10.38
2012 Toyota Camry, 4 cyl.	8.3	15.6	366.0	10.63
2011-12 Dodge Caravan, 6 cyl.	8.1	16.7	357.2	10.89
2014 Chevy Impala, 6 cyl.	8.1	16.3	357.2	10.89
2012-14 Ford Explorer, 4 cyl.	7.8	15.9	344.0	11.31
2013 Honda Accord, 4cyl.	7.7	15.8	339.6	11.45
2013 Nissan Altima, 4 cyl.	7.1	15.5	313.1	12.42
2012 Mercedes S Class, 6 cyl. (D)	7.0	15.3	308.7	12.60
2013 Toyota Avalon, 6 cyl.	6.8	15.3	299.9	12.97
2012 Mercedes C Class, 4 cyl.	6.8	15.3	299.9	12.97
2011-13 Ford F-150, 6 cyl.	6.5	15.3	286.7	13.57
2012-13 BMW 5 Series, 4 cyl.	6.1	14.5	269.0	14.46
2012-13 Chevy Camero, 6 cyl.	6.0	14.4	264.6	14.70
2009-12 Nissan Maxima, 6 cyl.	5.8	14.4	255.8	15.21
2012-12 BMW 3 Series, 4 cyl.	5.6	14.4	247.0	15.75
2011-13 Ford Mustang, 6 cyl.	5.3	14.0	233.7	16.64
2014 Chevy Corvette, 8 cyl.	3.9	12.1	172.0	22.62
2008-10 Dodge Viper, 10 cyl.	3.6	11.9	158.8	24.50

Avg, 12.89 ft/s^2