Fastest Path Speed Evaluations; Design vs. Actual Multilane Roundabouts

J. Tom Knostman, P.E.: City of Loveland **May 12, 2008**

I. Introduction

This paper contrasts the results of estimated fastest path speeds proposed under the modified UK methods detailed in NCHRP Report 572 (Maximum R1, R2 and R3 speeds) with field conditions for three, post-construction, two-laned roundabouts in Loveland.

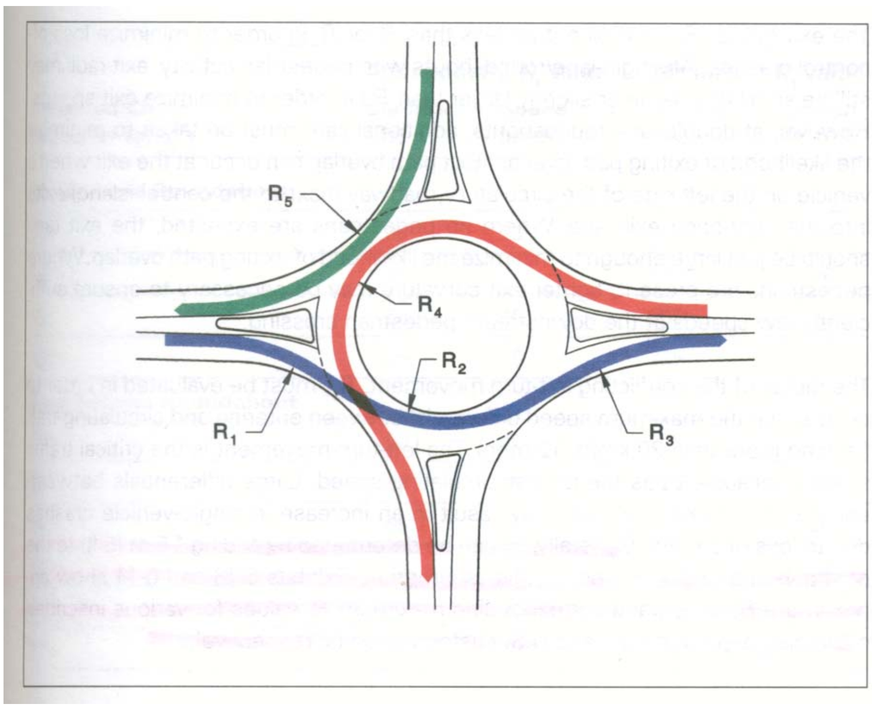


FIGURE 1 ROUNDABOUT TURNING RADII IDENTIFICATION

Significant discrepancies, as high as 17 miles-per-hour (mph), were found between design estimated and field documented speeds for the R1 entry movement. The average under- prediction of entry speed was 13 mph. This discrepancy is greater than the state target speed differential of 12 mph between entering and circulating traffic.

A. Roundabout Design: Mission Critical

The fastest, "race car" path into and through a roundabout is limited by the most constrictive arc created by the R1, R2 and R3 deflections as shown on Figure 1. The minimum radius of the arc superimposed on the fastest path and the superelevation of the pavement are then converted to an estimated maximum entry speed based on standard AASHTO Green Book equations. The premise of this modeling is to limit the speed differential between entering vehicles and those circulating the roundabout to 12 miles per hour or less. This is intended to limit the potential for rear-end accidents, but also functions to regulate the overall circulating speed and prevent drastic slowing in the R-2 movement around the central island.

The introduction to Chapter Six of the June 2000, FHWA Roundabout Informational guide states:

> Designing the geometry of a roundabout involves choosing between trade-offs of safety and capacity. Roundabouts operate most safely when their geometry forces traffic to enter and circulate at slow speeds. **Horizontal curvature and narrow pavement widths are used to produce this reduced speed environment.** Conversely, the capacity of the roundabout is negatively affected by these low-speed design elements. As the widths and radii of entry and circulatory roadways are reduced, so also the capacity of the roundabout is reduced.

The Foreword to the 2007 National Cooperative Highway Research Program (NCHRP) Report 572 states:

> Two key characteristics of the modern roundabout are (1) entering traffic that yields to circulating traffic and (2) **geometric constraints that slow entering vehicles**.

Item two in this statement confirms the importance of proper design to achieving slow (safe) entry speeds.

Because safety is at the forefront of roundabout design and is a function of entry and circulating speed, it is critical that an accurate method exist to predict speeds through the roundabout. Speed prediction should be able to accurately estimate the maximum fastest path and the 85-percentile entry speeds so that designers can make conscious decisions about how the roundabout will operate. It also needs to be stated that fundamentally the issue of fastest path is irrelevant when delay exist at the yield line.

B. City of Loveland Roundabout Experience

The City of Loveland, population approximately sixty thousand, was early to embrace roundabouts as an alterative intersection design that could improve safety while improving traffic operation. The City's first entry into roundabouts were two double-lane roundabouts on Rocky Mountain Avenue (Rdbts # 1 and # 2 on Figure 2) servicing a growing commercial district directly adjacent to Interstate 25 at US 34. These roundabouts, constructed in 1997, are radial in design and have had only three injury accidents since opening. This general success has allowed the City to pursue other roundabouts in the community which now has seven double-lane roundabouts, an equal number of single-lane roundabouts and numerous traffic calming circles. Loveland expects to double these numbers in the next ten years based on community growth and the excellent service from its existing roundabouts.

II. Problem Statement

Observations of entry speeds for recently constructed two-lane roundabouts within the City of Loveland prompted a review of the design techniques used to control fastest path speeds.

A. State of the Art Fastest Path Analysis

Fastest path modeling is considered to be a critical component of safe roundabout design. It is widely accepted that roadway geometrics control entry speed to a multi-lane roundabout and that excessive speeds (greater than 25 mph, FHWA Exhibit 6-4) increase the risk of accidents. The question is how to evaluate entry and circulation speed issues during design, prior to construction. Methods for delineating the fastest path into and through a roundabout at the design stage and converting this path to an estimated speed are delineated in NCHRP Report 572: Appendix G. Most US expert designers use this methodology, ignoring lane lines, producing higher maximum entry speeds.

Chapter 5 of NCHRP Report 572 presents a method, under the heading of Speed Analysis, "To improve the prediction of entry speeds" as a function of "path radius". This "path radius" is not linked to fastest path in the main text of the report and is in fact compared to only to 85-percentile speeds which are not fastest path speeds by definition. Maximum or fastest path typically not be represented in an average data set for a roundabout entry speeds because most drivers are not driving the fastest they can!

The ability to predict the 85-percentile speed may be of importance but should not be confused with fastest path entry speed. The method for developing the "path radius" used to predicted entry, circulating and exit speeds (V_1, V_2, V_3) is developed in Appendix G to the report. The title of Appendix G to NCHRP 572 is "Definitions for Estimating Fastest Path". This title contradicts the main text.

The entry speed reduction proposed in Chapter 5 of NCHRP Report 572 will not be considered because the reduction in maximum entry speed is solely function of V_2 circulating speed. This limited study finds the modified UK methods under-predict the fastest path speeds for both V_1 and V_2 and are therefore unreliable as input to an adjustment to the maximum entry speed.

B. Rocky Mountain Avenue

Rocky Mountain Avenue, a four-lane arterial road serving as a commercial feeder and west frontage road to I-25, is expected to grow to a peak AADT of 20 to 30-thousand vehicles by the year 2030. Four double-lane roundabouts were added to the Rocky Mountain Avenue in 2006 for a total of six roundabout intersections on the corridor. These four are north of the original two as shown on the Vicinity Map. The furthest north is currently only a two leg roundabout with the third leg to be added in the future and is not part of this study. The three roundabouts in this study shown on the Figure 2 below, and progressing from south to north, are identified as:

- Rdbt # 3: Medical Center of the Rockies South (MCR S)
- Rdbt # 4: Medical Center of the Rockies North (MCR N)
- Rdbt # 5: Kendall Parkway

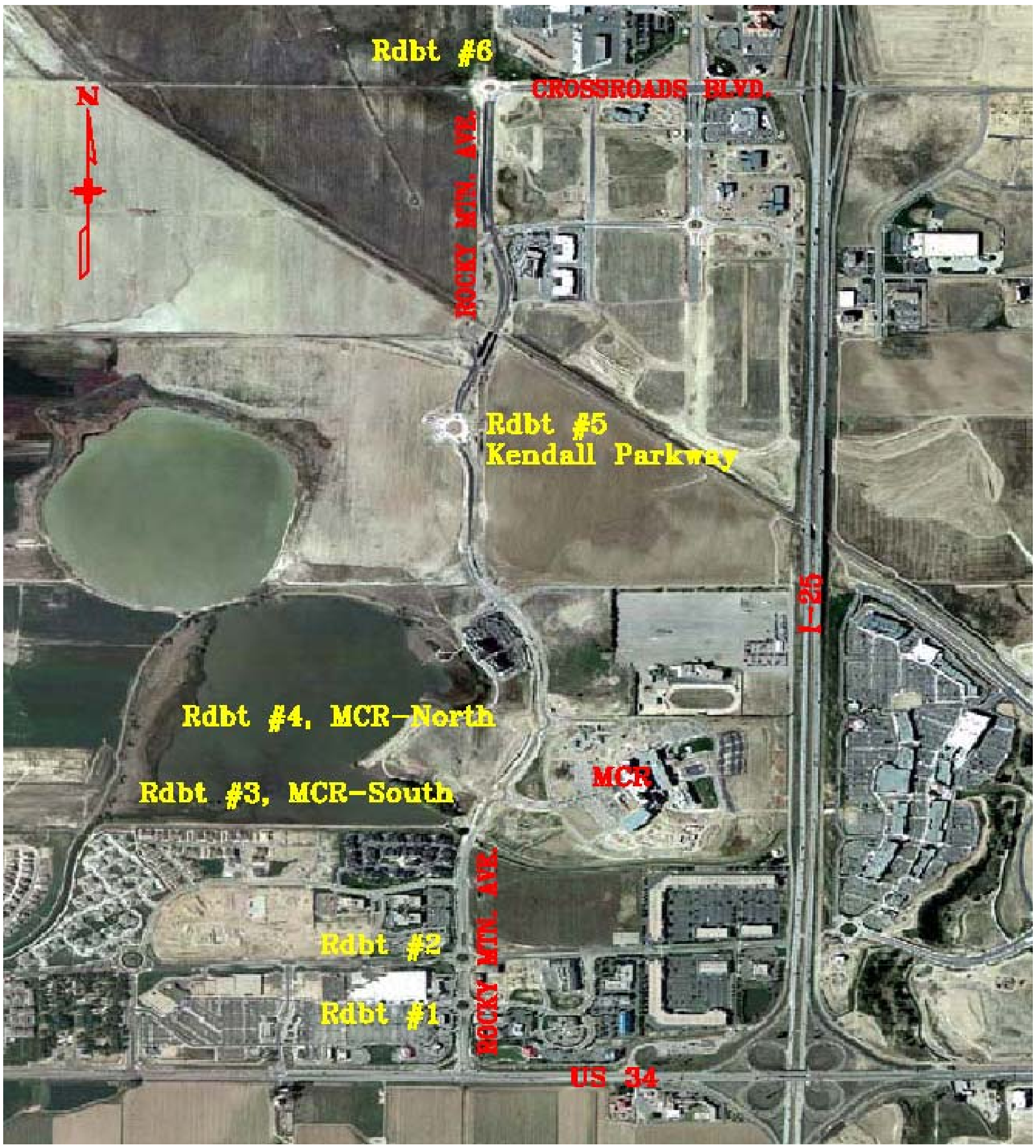
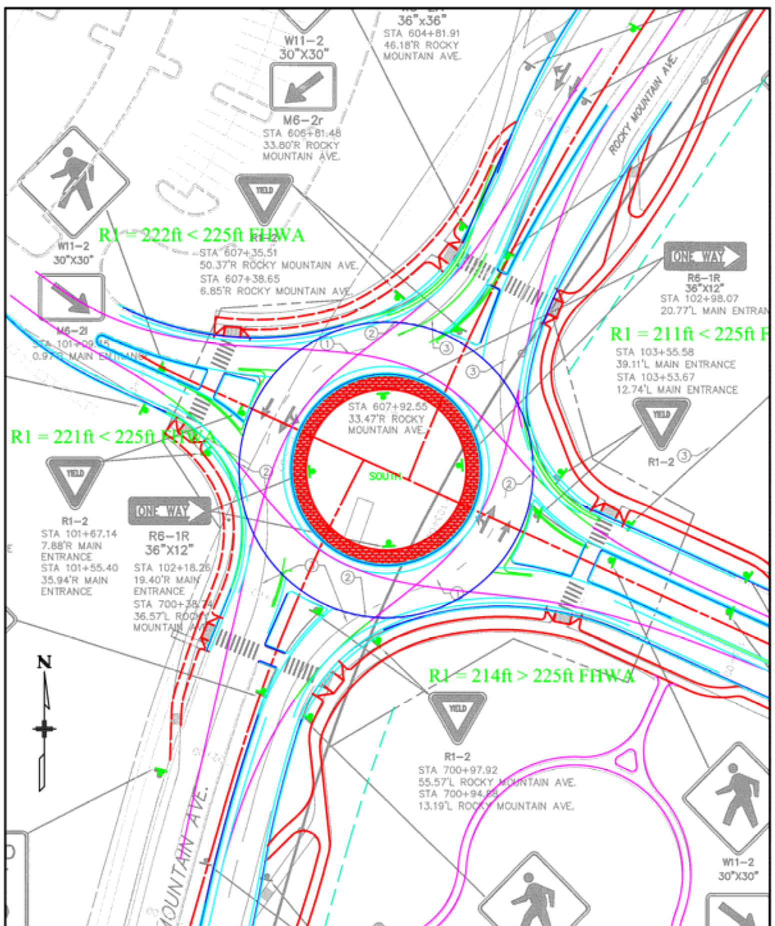


FIGURE 2: Vicinity Map of Rocky Mountain Avenue Roundabouts

C. Design Methodology

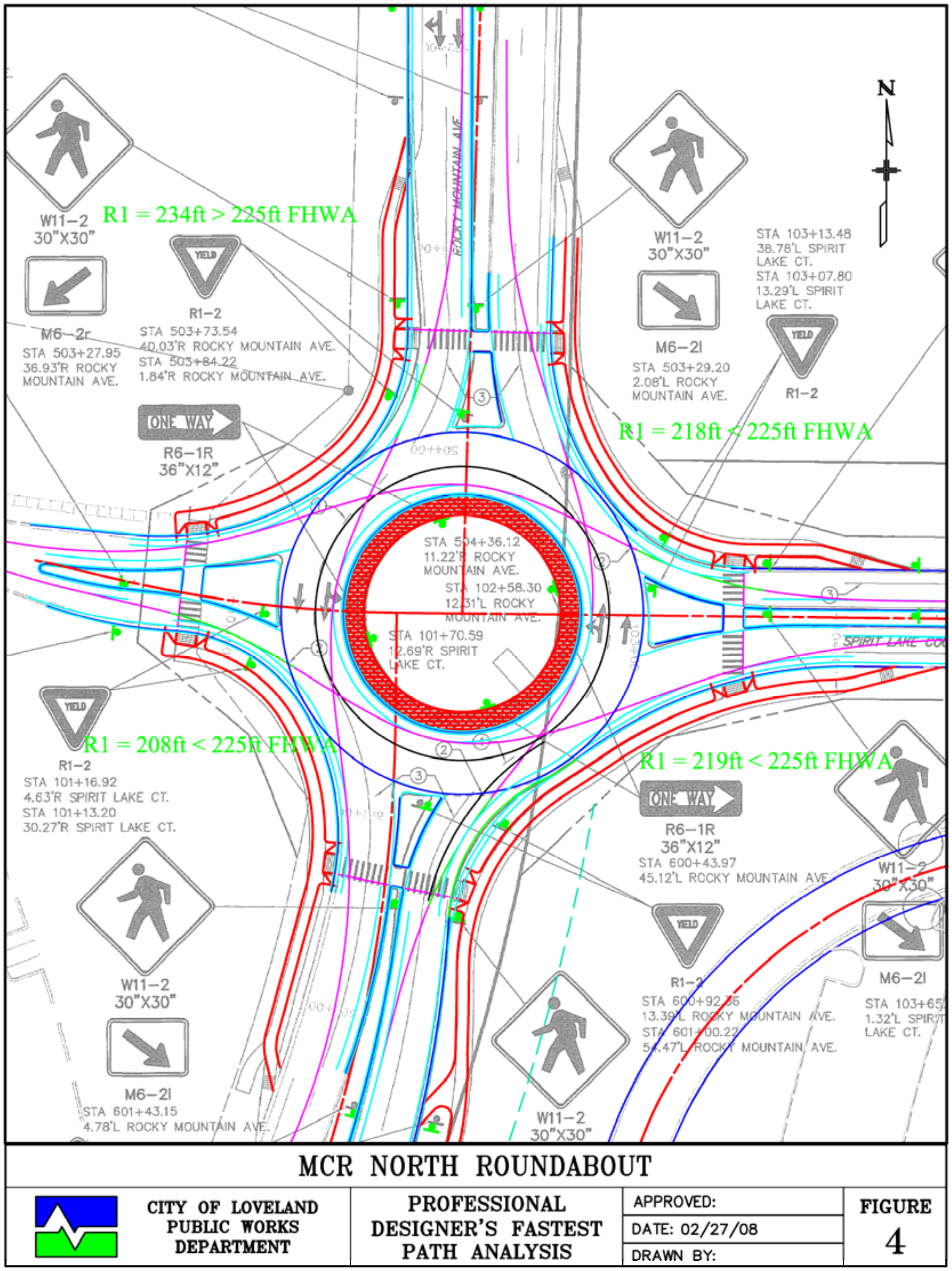
The designs for the three roundabouts were completed by professionally recognized Colorado civil design firms with professional oversight from nationally recognized design experts. Fastest path evaluations received significant attention during this process. Fastest path layouts are shown on Figures 3 through 5 below, for the roundabouts mentioned above, respectively. Both designers used the methods delineated in NCHRP Report 572 (Appendix G) using 5-foot offsets from the curb face. No values for R2 and R3 were documented with the design reports.

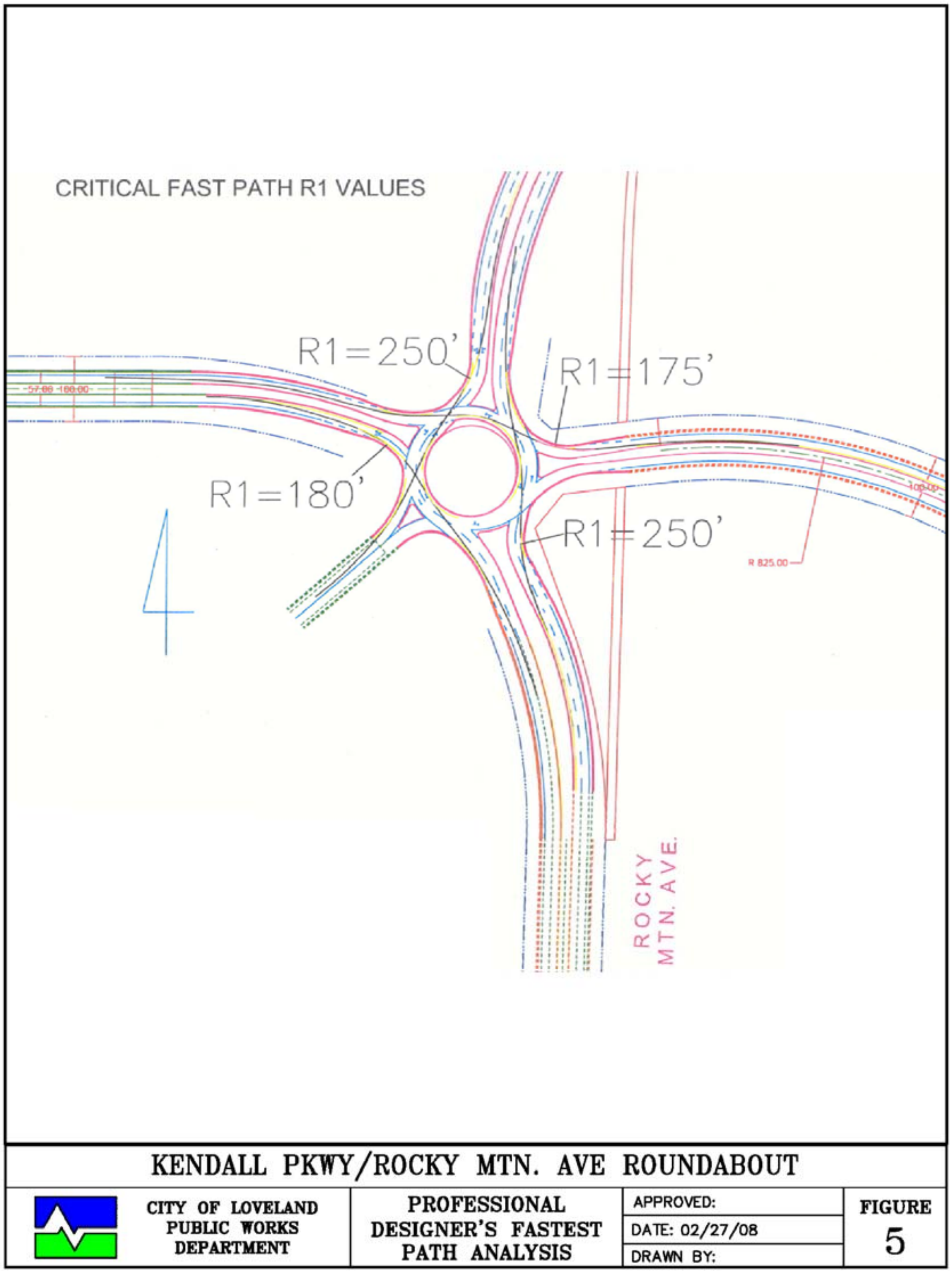
The professional designer for the MCR roundabouts used the FHWA criteria of a maximum 225-foot R1 arc to control entry speed to less than approximately 26.5 mph. The professional designer for the Kendall Parkway roundabout used a maximum 250-foot arc to control entry speed to less than approximately 28 mph.



MCR SOUTH ROUNDABOUT

CITY OF LOVELAND PUBLIC WORKS DEPARTMENT	PROFESSIONAL DESIGNER'S FASTEST PATH ANALYSIS	APPROVED: DATE: 02/27/08 DRAWN BY:	FIGURE 3


N
W11–2
30"X30"
R1 = 234ft > 225ft FHWA
R1–2
M6–2r
STA 503+27.95
36.93'R ROCKY
MOUNTAIN AVE.
STA 503+73.54
40.03'R ROCKY MOUNTAIN AVE.
STA 503+84.22
1.84'R ROCKY MOUNTAIN AVE.
ONE WAY
R6–1R
36"X12"
ROCKY MOUNTAIN AVE
W11–2
30"X30"
M6–2l
STA 503+29.20
2.08'L ROCKY
MOUNTAIN AVE.
STA 103+13.48
38.78'L SPIRIT
LAKE CT.
STA 103+07.80
13.29'L SPIRIT
LAKE CT.
R1–2
R1 = 218ft < 225ft FHWA
STA 504+36.12
11.22'R ROCKY
MOUNTAIN AVE.
STA 102+58.30
12.31'L ROCKY
MOUNTAIN AVE.
STA 101+70.59
12.69'R SPIRIT
LAKE CT.
SPIRIT LAKE
R1 = 208ft < 225ft FHWA
R1–2
STA 101+16.92
4.63'R SPIRIT LAKE CT.
STA 101+13.20
30.27'R SPIRIT LAKE CT.
R1 = 219ft < 225ft FHWA
ONE WAY
R6–1R
36"X12"
STA 600+43.97
45.12'L ROCKY MOUNTAIN AVE.
W11–2
30"X30"
M6–2l
STA 600+92.36
13.39'L ROCKY MOUNTAIN AVE.
STA 601+00.22
54.47'L ROCKY MOUNTAIN AVE.
W11–2
30"X30"
M6–2l
STA 601+43.15
4.78'L ROCKY MOUNTAIN AVE.
W11–2
30"X30"
MCR NORTH ROUNDABOUT
CITY OF LOVELAND
PUBLIC WORKS
DEPARTMENT
PROFESSIONAL
DESIGNER'S FASTEST
PATH ANALYSIS
APPROVED:
DATE: 02/27/08
DRAWN BY:
FIGURE
4



III.Fast Path Evaluation - Post Construction

To compare the actual versus estimated fastest path speeds, actual speeds driven through the roundabout were compared with the estimated fastest path speeds using state of the art fastest path design methods as detailed above.

A. Drive Fast!!!

The most obvious method to test post-construction fastest path was to get in a car and drive as fast as one dares through the new roundabouts. This was felt to be safe due to the lack of cross traffic on the roundabouts. The MCR roundabouts are only connected to the hospital and none of the minor roads are currently connected to the Kendall Pparkway roundabout.

On the morning of Sunday November 11th, 2007 between 9:00 and 9:30, with a full tank of gas and a half a box of powdered doughnuts, and my son armed with a video camera, we set out to drive fast. The roads were clear of sand, the weather cool and crisp and the family station wagon, a SAAB 9^5 Aero equipped with a four-cylinder 2.3 liter, turbo-charged engine, ready to test its metal.

The study involved three north-south passes through the roundabout train, my son recording the speedometer as I called out the position (R1, R2 or R3). We quickly realized that holding the camera still on the speedometer was almost impossible and I needed to call out the minimum speed forced by the corresponding curve. Thus the level of accuracy implied is a function of the method of data collection and the accuracy of the speedometer. Table 1 presents the observed field speed observations and contrasts them with the designer's prediction and the City calculation of the new NCHRP methodology. Note that under the new NCHRP methodology the maximum entry speed would be the minimum of V1 or V1 as a function of V2, the distance between V1 and V2 and the deceleration between the two. As can be seen, the new NCHRP method theoretically does not control the entry speed for these roundabouts.

TABLE 1: Maximum Predicted vs. Field Speeds

Roundabout	Direction	Design Est. V1 Speed	NCHRP 572 V1(V2) Speed	MAXIMUM ACTUAL SPEED (mph) V1Speed	V2 Speed	V3 Speed
Kendall	SB	28	28.0	38	31	32
MCR N	NB	26	28.8	40	33	35
MCR S	SB	26	29.3	39	35	38
MCR S	NB	26	28.6	37	31	37
MCR N	SB	27	28.0	41	37	39
Kendall	NB	28	39.3	45	45	50

B. Independent Fastest Path Evaluation

An independent fastest path evaluation was completed by the City of Loveland as part of this study to estimate / verify arc radii of the three controlling arcs (R1, R2 and R3, reference Figure 1) on an independently produced fastest path. This was done in AutoCad using a spline line and 5-foot offsets in accordance with NCHRP Report 572 Appendix G over the plan view of the original design. The independent verification appears to confirm the original design (within 35-feet or 2 mph) except for the northbound movement through the Kendall Parkway roundabout where the fastest path was almost 90-feet greater than the professional design or a difference of almost 5 mph. Table 2 presents the R1 arc radius estimate produced by the professional designer compared with the City developed R1 radius. Table 2 also presents the R2 and R3 arc radii and the d_{12} length between R1 and R2 for use in evaluating the maximum entry speed based on the new 572 Report recommendations.

TABLE 2: Standard Arc Radii

	Professional Design R1	Measured 5' Std. Arc R1 (ft)	R2 (ft)	R3 (ft)	d_{12} (ft)
Kendall SB	250	235	79	607	144
MCR N SB	234	267	155	376	100
MCR S SB	222	236	145	6400	115
MCR S NB	214	183	131	654	115
MCR N NB	219	228	105	603	125
Kendall NB	250	339	406	627	100

The fastest path spline was then adjusted at the R1 and R2 control positions to create a spline with 2-foot and 0-foot offsets from the curb face at approximately the pedestrian crosswalk and a point on the central island approximately perpendicular to the fastest path. This was done to evaluate fastest path speeds for a more aggressive fastest path spline and to see if this could produce a more accurate speed model when compared with the actual speeds. Arcs R1, R2 and R3 radii for these more aggressive paths are presented in Tables 3 and 4, respectively.

TABLE 3: 2-Foot Offset Arc Radii

	Measured Arc 2' offset at R1 & R2 R1 (ft)	R2 (ft)	R3 (ft)
Kendall SB	238	96	583
MCR N SB	326	185	424
MCR S SB	302	153	6500
MCR S NB	226	144	750
MCR N NB	330	104	642
Kendall NB	586	819	857

TABLE 4: 0-Foot Offset Arc Radii

	Measured Arc 0' offset at R1 & R2 R1 (ft)	R2 (ft)	R3 (ft)
Kendall SB	400	87	530
MCR N SB	451	228	523
MCR S SB	434	186	10700
MCR S NB	247	162	902
MCR N NB	452	123	831
Kendall NB	623	1037	947

C. Actual vs. Modeled Results Compared

Figures 6 through 8 below graphically present the results of this study. Figure 6 presents the predicted R1 fastest path speeds as predicted by the design professional (row 1; plum) versus the maximum R1 entry speed from the test drive data (row 5; aqua). Figure 6 also shows the City of Loveland's independent fastest path analyses using NCHRP Report 572 (Appendix G) to develop a spline with all offsets at 5-feet and with R1 and R2 offsets at 2 and 0-feet on rows two, three and four, respectively. On Figure 6, the roundabouts are identified on the x-axis, the fastest path method on the y-axis and the actual or predicted speed is represented by the relative height of the bar on the z-axis.

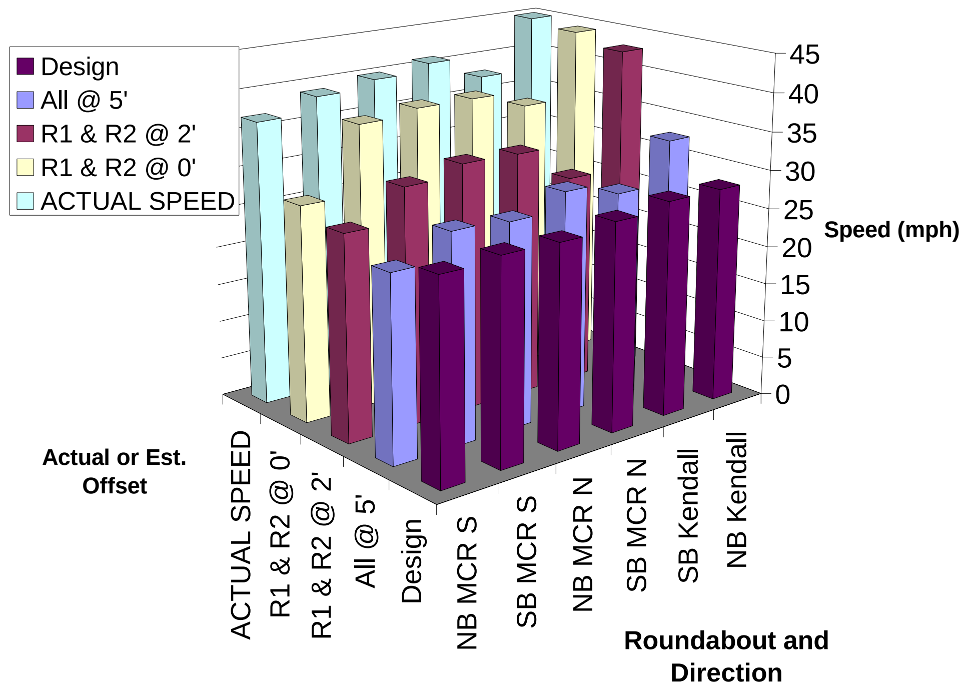


FIGURE 6: Maximum R1 Entry Speed

As discussed above, the professional estimate and City verification, using standard fastest path procedures with a 5-foot offset, appear to coordinate well. This is does not hold true for NB Kendall Parkway where the designer predicted a maximum entry speed of 28 mph and the City estimated 33 mph. Neither of these is close to the actual driven speed at 45 mph (without even squealing the tires). This trend carries through the entire roundabout study group with the field driven entry speeds all greater than 35 mph. This is significantly above the recommendation of 28 mph for urban, double-lane design (FHWA Exhibit 6-14) and the professionally estimated speeds between 26 and 28 mph. As can be seen on Figure 6, the best correlation with the this field data is the 0-foot offset at the R1 and R2 positions and 5-foot elsewhere although the northbound entry to MCR South was still almost 9 mph less than actual. On average the 0-foot offset estimate was 3 mph less than actual driven speeds. This might be a starting point for further research on predicting the maximum speeds.

Figure 7 represents the field driven speeds through R2 versus City predicted speeds at 5, 2 and 0-foot offsets. No estimates were provided by the professional designers. On average the actual V2 driven speeds were 13 and 11 mph greater than those estimated with the 5-foot and 0-foot offset splines, respectively. The 0-foot offset number for the NB Kendall Parkway movement was not included in the average as it was significantly above the actual and would skew the average. Although the modified spline with a 0-foot offset provided only a slight improvement for the R2 speed estimate, it should be noted that it is integral in relaxing the spline path through the R1 estimate area and therefore should be maintained.

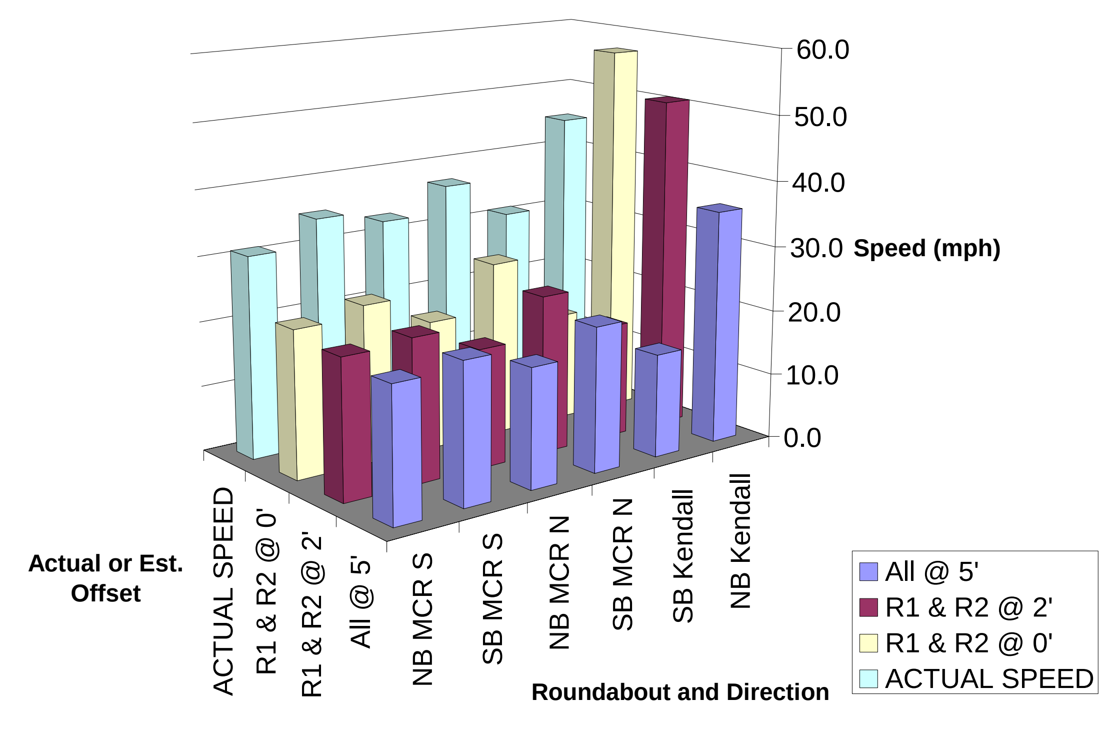


FIGURE 7: Maximum R2 Speed

This highlights the critical nature of a visible curb face and truck apron on the central island that forms sufficient deterrent to drive over traffic that could further flatten the fastest path. The City of Loveland uses a 4-inch high mountable (1:1) curb face with a colored concrete truck apron surface.

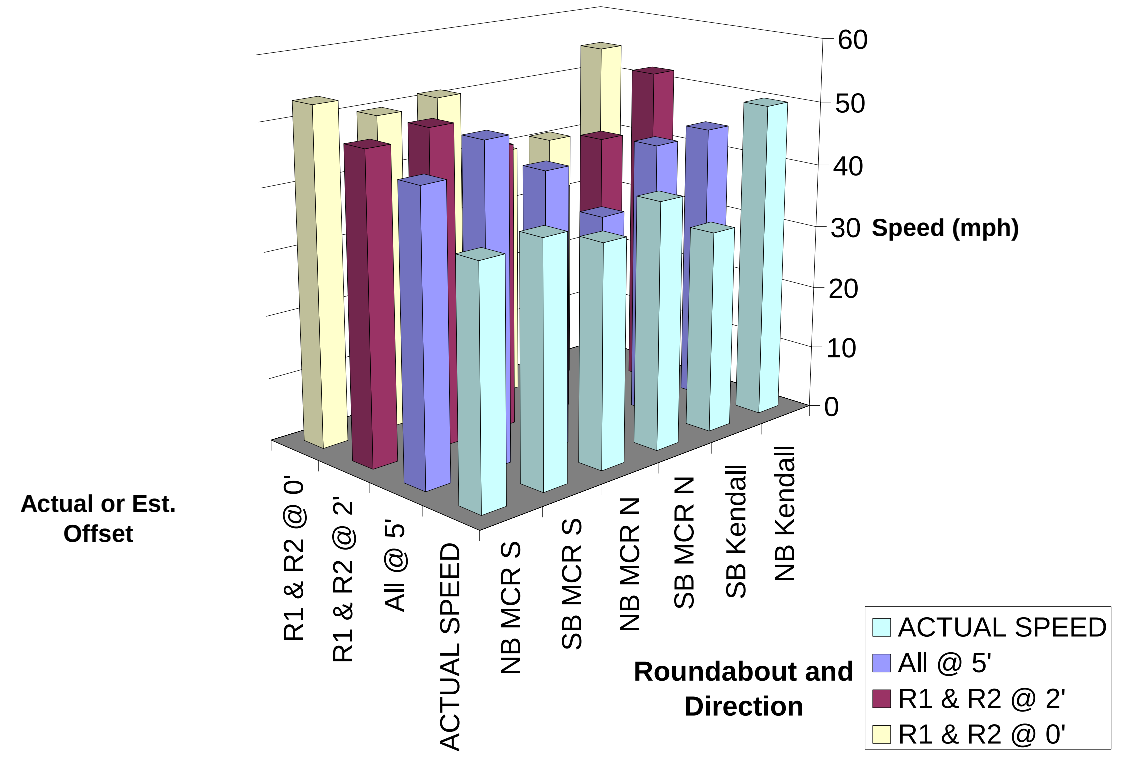


FIGURE 8: Maximum R3 Exit Speed

Figure 8 represents the field driven speeds through R3 versus City predicted speeds at 5, 2 and 0-foot offsets for the R1 and R 2 positions. No estimates were provided by the professional designers. On average the actual R3 driven speeds were 4 and 10 mph less than those estimated with the 5-foot and 0-foot offset splines, respectively. The estimated speeds for the southbound MCR South movement were truncated at 50 mph and were not included in the average as they are significantly above the actual and would skew the average. It should be noted that relaxing the spline path at R1 and R2 significantly increases the predicted exit speeds and is less accurate than the standard 5-foot offset. It appears that the proximity of the R2 limits the exit speed at R3. This is a fascinating observation to be discussed in another paper.

IV. Conclusion

In the light that:

- The majority of the roundabout design industry (minus NYSDOT) is fixated on fastest path as a design tool for the control of entry and circulating speed.
- Fastest path design control is deemed critical to controlling speeds and thus promoting safety of roundabout design.
- Excessive deflection and lane width control is a detriment to roundabout capacity.
- Excessive deflection can cause excessive slowing leading to rear end crashes.
- Lane width is controlled by the design vehicle which is typically a WB-67 tractor trailer combo.
- Newly promoted NCHRP 572 modifications to estimate the entry path radius and speed appear to be better suited to predicting 85-percentile entry speeds.

The goal of this study is to start a conversation about the reliability of fastest path entry speed estimate techniques and its usefulness to predict the maximum entry speed during design. It is fully acknowledged that the limited data set and uncalibrated speed monitoring device (my observation of my cars speedometer) is not ideal for a true study. Nonetheless, I offer the following conclusions to the roundabout design community:

A. Use of the Current Modeling Convention is Flawed

The use of the modified UK fastest path prediction method is significantly flawed with estimates better representing the 85-percentile speeds rather than a true fastest path. Modifications proposed in Chapter 5 of NCHRP 572 for entry speeds are compared to 85-percentile speeds and thus only appropriate for prediction of such and not fastest path.

B. FHWA (Exhibit 6-4) Maximum Speed Recommendations are Unattainable

The basis for use of fastest path in the design of roundabout as stated in the FHWA informational guide:

> On the fastest path, it is desirable for R1 to be smaller than R2, which in turn should be smaller than R3. This ensures that speeds will be reduced to their lowest level at the roundabout entry and will thereby reduce the likelihood of loss of control crashes. It also helps to reduce the speed differential between entering and circulating traffic, thereby reducing the entering-circulating vehicle crash rate. However, in some cases it may not be possible to achieve an R1 value less than R2 within given right-of-way or topographic constraints. In such cases, it is acceptable for R1 to be

greater than R2, provided the relative difference in speeds is less than 12 mph and preferably less than 6 mph.

As shown in Table 1 and on Figure 6 the above statement appears to be unattainable for this sample set. Additionally, the dependence on the R2 curvature to be smaller than R1, as prescribed by NCHRP 572 to control entry speeds, is undesirable per the guidance above. Creating a large inscribed diameter to promote greater R1 deflection is undesirable because of higher circulating speeds and increased ROW cost. Creating flattened R2 pathways to raise circulating speeds is similarly not the solution as this promotes higher entry speeds as demonstrated in the northbound Kendall Parkway design where the through speed was as high as 45 mph.

Simply put, it is desirable to be able to predict the actual fastest path entry and circulating speeds. It is not realistic to use 12 mph let alone 6 mph as the maximum differential between entry and left turn circulating speeds. Of course if there is delay at an entry, all of this fastest path “stuff” is irrelevant. But even a busy roundabout will have periods where there is no queue at the yield line. **Fundamentally the design community must acknowledge fastest path entry speeds on multi-lane roundabouts will typically be greater than 30 to 35 mph.**

C. Must Balance Truck Entry and Entry Path Concerns

Because roundabout design is a balance between opposing objectives, there will be no absolute design method directive put forward here. Each community and agency must decide for itself what the more important design concerns are. As such, and barring the ability to limit truck traffic (which Loveland has found to be a failure with expensive remedial consequences), one must design for the largest anticipated truck traffic (typically a WB-67). The designer must also decide if trucks and cars or trucks and trucks should be allowed to traverse the design side by side. These decisions will be critical to:

- The diameter of the roundabout
- The deflection at entry
- and ultimately the width of entry

All these parameters must be balanced with the desired maximum entry speed and desired capacity while avoiding entry path overlap. If all these design issues are interrelated, then it is fantasy to be making these decisions based on the current fastest path estimate methodology!

D. Proposed Modification

To conclude this overblown excuse for me to be able to drive fast through roundabouts, I am proposing:

1. Entry speed estimates using the currently accepted NCHRP 572 fastest path method are radically too low.

2. The current NCHRP 572: Appendix G with 5-foot offsets "fastest path" speed estimating method is better suited for predicting 85-percentile entry, circulating and exit speeds in multi-laned roundabouts.
3. The prediction of 85-percentile entry speed is a more appropriate parameter to use in the design of a roundabout to maintain a balance with other concerns such as speed consistency.
4. NCHRP should conduct a new study to understand the correlation between the methods delineated in Appendix G to Report 572 and actual fastest path speeds so that a better method to estimate of fastest path can be developed if this continues to be important to roundabout design.