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Impact of Geometric Factors on the Capacity of Single-Lane Roundabouts

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Abstract

Roundabout capacity is primarily estimated by gap-acceptance or by geometric models. The 2010 Highway Capacity Manual (HCM 10) uses a gap-acceptance model developed by Siegloch with empirically derived values of critical gap and headway for single-lane and two-lane entries. A geometric capacity model was developed by Kimber and Hollis that diverged from gap-based models. The capacity of up to four lane entries was empirically derived from six geometric parameters. In 2012 capacity data were collected as part of the FHWA project, Assessment of Roundabout Capacity Models for the Highway Capacity Manual. These data were used to produce HCM6, an update of the HCM 2010. In HCM6, a capacity curve was fitted through all the capacity data for single-lane roundabouts. The large scatter of data about the mean capacity line suggests that the single-lane roundabouts may be separated into different geometric types to improve accuracy. To investigate this hypothesis, the capacity data were separated into two geometrically distinct types of single-lane roundabouts: smaller, compact and larger, curvilinear. The range of data for the disaggregated and aggregated data was compared. Also, a capacity line was derived for each type using the geometric capacity model and compared with the disaggregated data with the HCM6 method. The results demonstrate that differences in geometry, absent in HCM6, explain the wide data range. This was further confirmed by the geometric model that gave a good fit to both sets of data. These results indicate that the accuracy of capacity prediction is improved by including geometric variation.

US single-lane capacity data were collected in 2012 as part of the FHWA project to update HCM 10 (*1*) to the HCM6 (*2*). The capacity data were collected at 11 sites: five in Carmel, Indiana; two in New York State; three in Washington State; and one in Colorado.

Each data point is the observed saturated entry flow plotted against the observed circulating flow for periods of 1 min (Figure 1) (*3*). The data show a wide range in the observed capacities for all circulating flows. At circulating flows of 200 and 700 passenger cars per hour (pc/h), the observed entry capacities vary between 300 and 1,200 pc/h, and between 300 and 1,600 pc/h, respectively.

It is evident that an average capacity curve fitted to this wide range of data will not give good estimates of capacity for a given circulating flow. Consequently, there is a significant risk of overestimating or underestimating capacity, which may distort the design and evaluation process.

This wide range of capacity suggests that single-lane roundabouts may be separated into different geometric types.

To investigate this hypothesis, the observed capacity data were disaggregated into two distinct types of single-lane roundabouts—the smaller, more compact roundabouts and those with larger, more curvilinear geometry. Kimber's six geometric parameters allowed for distinguishing between the two types of roundabouts as described later in Table 3 and Figures 4 and 5.

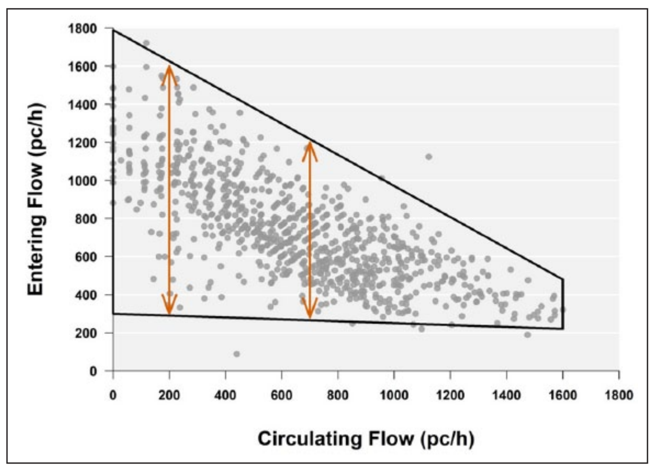

Figure 1. Aggregated single-lane field-collected HCM6 capacity data.

To test whether the derivation of capacity from the six geometric parameters gave a good fit to the data, the

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Table 1. Single-Lane Data Set in HCM6

Subarea	Site	Site code	Usable data points
Carmel, IN	136th Street/Keystone Parkway NB	IN12-E	4
Carmel, IN	136th Street/Keystone Parkway NB	IN12-S	71
Carmel, IN	96th Street/Ditch Road	IN07-E	31
Carmel, IN	96th Street/Ditch Road	IN07-S	10
Carmel, IN	96th Street/Westfield Boulevard	IN08-N	13
Carmel, IN	116th Street/Spring Mill Road	IN09-S	54
Carmel, IN	116th Street/Spring Mill Road	IN09-W	139
Carmel, IN	106th Street/Spring Mill Road	IN10-E	51
Carmel, IN	106th Street/Spring Mill Road	IN10-N	32
Carmel, IN	106th Street/Spring Mill Road	IN10-W	32
Carmel, IN	Subtotal	n/a	437
New York State	US 9/Warren Street/Hudson Avenue/Glen Street	NY07-S	71
New York State	US 9/Warren Street/Hudson Avenue/Glen Street	NY07-W	92
New York State	US 9/Warren Street/Hudson Avenue/Glen Street	NY07-E	65
New York State	US 9/Warren Street/Hudson Avenue/Glen Street	NY07-NW	13
New York State	US 9/Warren Street/Hudson Avenue/Glen Street	NY07-NE	1
New York State	Curry Road (SR 7)/Hamburg Street (SR14)	NY08-N	9
New York State	Curry Road (SR 7)/Hamburg Street (SR14)	NY08-W	21
New York State	Subtotal	n/a	272
Washington State	SR 166/Mile Hill Drive/Bethel Avenue	WA04-E	26
Washington State	SR 166/Mile Hill Drive/Bethel Avenue	WA04-N	16
Washington State	Lundeen Park Way/Callow Road	WA33-E	4
Washington State	Lundeen Park Way/Callow Road	WA33-W	13
Washington State	SR 20 Spur/Commercial Avenue	WA34-E	7
Washington State	SR 20 Spur/Commercial Avenue	WA34-N	5
Washington State	Subtotal	n/a	71
Colorado	Eby Creek Road/US 6 (Grand Avenue)	CO01-W	39
All Sites	Total data points	n/a	952
All Sites	Data points with one or more pedestrian events	n/a	133
All Sites	Total usable data points	n/a	819

uncalibrated geometric capacity model was used to predict the capacity line for each data set, and was then compared with the HCM6 exponential capacity lines fitted to each data set.

The 2012 single-lane data set shows that a significant quantity of data was collected from the five Carmel sites (437 usable data points), and also from the New York Glens Falls-US 9/Warren Street roundabout (242 usable data points) (Table 1) (*3*). This constitutes 72% of the total data collected for single-lane roundabouts.

The Glens Falls, NY-US 9/Warren St. roundabout and the Carmel roundabouts have distinctly different geometry. Glens Falls has smaller, more compact geometry, whereas the Carmel sites are large and curvilinear. The observed capacity data for each of these geometrically different types of roundabout were selected (Figure 2).

The data set for each site is distinct and the range of data for each geometric type is considerably less than the HCM6 aggregated data seen in Figure 1.

The relationship between the difference in the geometry and the difference in the capacity data between these two roundabout types will be examined in detail using both Kimber's uncalibrated geometric model and the uncalibrated and calibrated HCM6 model. However, this is preceded by a summary overview of each model.

The HCM6 calibrated model utilized the locally measured follow-on times from the New York and Carmel roundabouts (Table 2).

Overview of the Two Capacity Models

UK Geometric Capacity Model

The UK Transport Research Laboratory observed saturated capacity data at 86 roundabouts, collecting a total 11,000 min of data. They also conducted test track experiments on 35 geometric parameters to identify those that most affected capacity. Six of the 35 variables were found to significantly

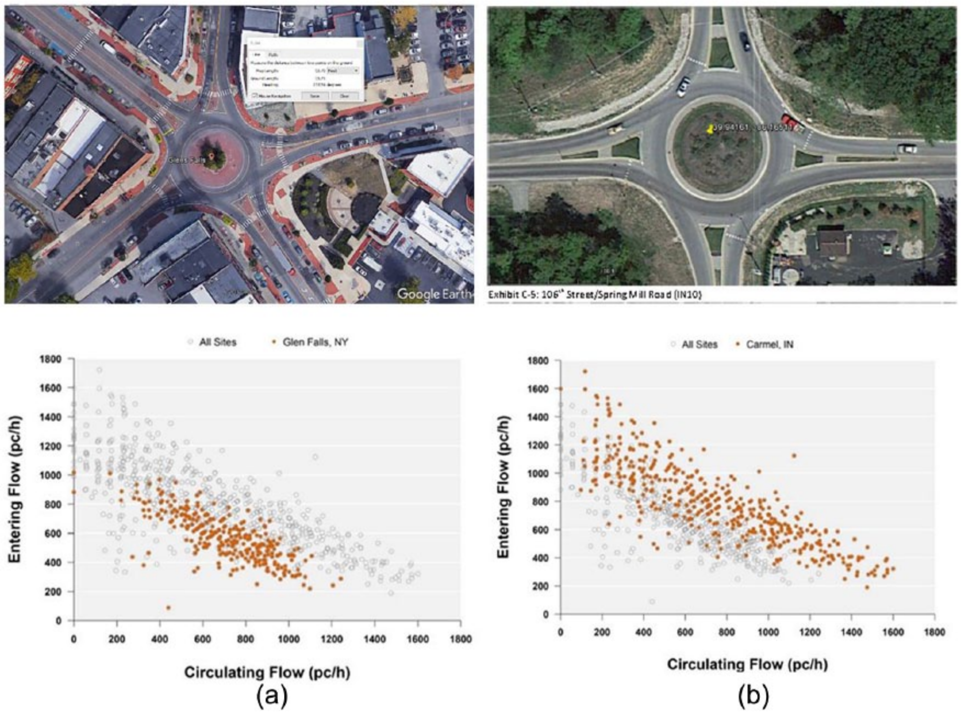


Figure 2. Capacity points for (*a*) smaller single-lane roundabout, Glens Falls, NY-US 9/Warren Street, and (*b*) representative larger curvilinear roundabout, Carmel, IN.

Table 2. Single-Lane Follow-on Times in HCM6

Site	Number of observations, n	Mean	Standard deviation
CO01-W	83	2.8	1
CO49-W2	4	2.9	0.9
IN07-E	40	2.5	1.1
IN07-S	38	2	0.8
IN08-N *	69	1.7	0.7
IN09-E	433	2.9	1.3
IN09-S	136	2.2	1.1
IN09-W	192	2.3	0.7
IN10-E	189	2.1	0.8
IN10-N	26	2.2	0.9
IN10-W	49	2	0.6
IN12-E	45	1.9	0.9
NY07-E	243	2.9	1
NY07-NW	141	2.8	0.9
NY07-NE	115	3	1.1
NY07-S	271	2.9	1
NY07-W	327	2.7	1.1

Averaged 'local' follow-on times for carmel and NY from HCM6 data:
IN07-E, S: 96th at Ditch Rd.: Ave. f = 2.26 s
IN08-N: 96th at Westfield: Ave. f = 1.70 s
IN09-S, W: Spring Mill Rd. at 116th: Ave. f = 2.2 s
IN10-E, N, W: Spring Mill Rd. at 106th: Ave. f = 2.09 s
IN12-E: Keystone Pkwy.: Ave. f = 1.90 s
NY07: Glens Falls/Warren/Hudson: Ave. f = 2.84 s

*IN09-E was removed from the weighted averages as there are no capacity data. Therefore, the follow-up time at IN09-E was not used for local calibration for Carmel sites. Similarly, this was applied to Kimber: the geometric parameters of IN09-E were not included.

Table 3. The Six Statistically Significant Variables of Roundabout Design

Geometric parameter	Symbol	Data range	Unit
Entry width[2]	e	3.6–16.5	Meters
Approach half width	v	1.9–12.5	Meters
Effective flare length	l’	1.0–∞	Meters
Entry radius	r	3.4–∞	Meters
Entry angle	ϕ	0.0–77	Degrees
Inscribed circle diameter	D	13.5–171.6	Meters

affect capacity of each entry (24 for a four-leg roundabout) (Table 3) (*4*).

The data from the 86 sites were used to directly relate capacity to each of the six geometric parameters. The result was Kimber’s capacity model, named after the head of the research team. The model is linear, as it was not possible to demonstrate any degree of nonlinearity. The straight line fits accounted for more than 90% of the variance in the capacity.

Kimber’s analytical framework was based on statistical principles, utilizing regression analysis to determine the most important geometric factors that have significant influence on the entry capacity. The model was derived as explicit functions of geometric factors in terms of the associations among them. The model coefficients were then jointly optimized by regressing the entry capacity on the independent variables.

The observed circulating flows Q_c were between 0 and 4,700 pc/h.

The entry capacity $Q_e = k\left(F - f_c Q_c\right)$
where

$$k = 1 - 0.00347\left(\phi - 30\right) - 0.978\left(\left(\frac{1}{r}\right) - 0.05\right),$$

$$F = 303x_2,$$

$$f_c = 0.210 t_D\left(1 + 0.2x_2\right),$$

$$t_D = 1 + \frac{0.5}{1 + \exp\left(\frac{D - 60}{10}\right)},$$

$$x_2 = v + \frac{e - v}{1 + 2S},$$

$$S = \frac{1.6\left(e - v\right)}{l'},$$

and *e, v, l’, D*, and *r* are in meters (or feet), ϕ in degrees, and Q_e and Q_c in pc/h.

These important geometric relationships have varying degrees of influence on capacity (Table 4). However, it is noted that the purpose of this study is not to examine the sensitivity of capacity to each geometric variable, but to determine if the geometric model may explain the wide variation in single-lane capacity data and lead to an improvement in capacity estimation (*5*).

HCM Model Development

The HCM 2010 roundabout capacity model was derived from directly-measured capacity data collected in 2003. A nonlinear (negative exponential) regression line was fitted to the data. The HCM 2010 recommends local calibration of capacity models to reflect local behavior as a means of providing more accurate capacity prediction. To accomplish this, it specifies a calibration procedure using the observed/measured average critical headway and follow-up headways. The *Y* intercept and exponential coefficient, or slope and curve of capacity line, are adjusted using these gap parameters.

$$Q_e = 1130.\exp\left(-0.0010Q\_c\right)$$

With local calibration, the equation becomes

$$Q\_e = A.\exp\left(-B \cdot Q\_c\right)$$

where

$$A = \frac{3600}{t_f}$$

$$B = \left(t_c - t_f / 2\right) / 3600$$

t_f is the follow-up headway and t_c is the critical headway.

HCM 2010 Update: HCM6

The HCM 2010 update, HCM6, retains the 2010 model form (Siegloch) (*6*). The HCM6 capacity line was developed by fitting an exponential line to the data and then anchoring the *Y* intercept to a value derived from the average observed follow-up times of all the collected data. The average follow-up time was 2.6 s, and resulted in a *Y* intercept of 1,380 pc/h.

$$Qe = 1380.\exp\left(-0.00102Qc\right)$$

With local calibration, the equation becomes

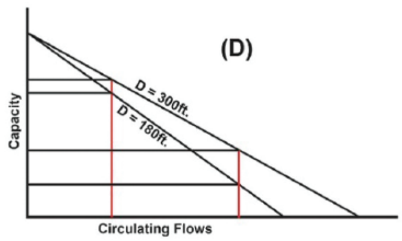
Table 4. Geometric Model Variables

Three Major Capacity Variables

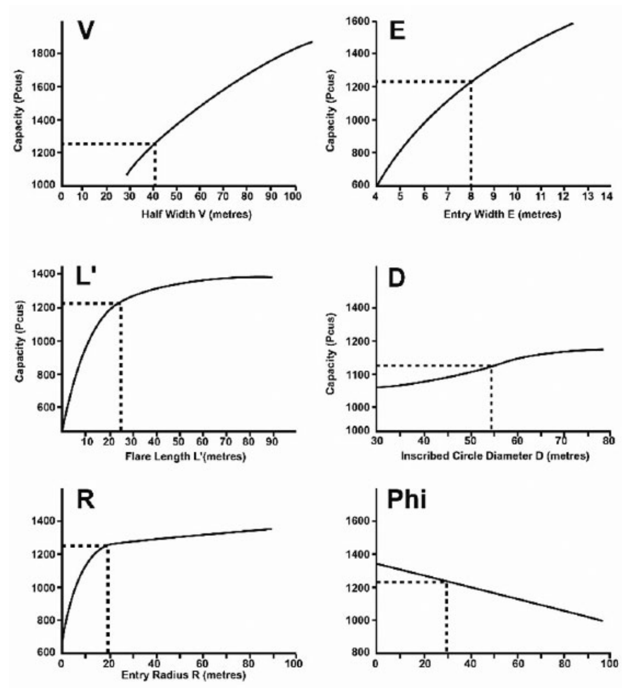
- Entry Width (E)
- Approach Width (V)
- Effective Flare Length (L')

Three Minor Capacity Variables

- Entry Radius (R)
- Entry Angle (ϕ)
- Diameter (D)



Six geometric inputs



$$Qe = A.\exp\left(-0.00102Qc\right)$$

where

$$A = 3600 / t_f$$

t_f is the measured average follow-up time for that region.

Although the HCM 2010 used both the critical gap and the follow-up time for calibration to local conditions, the HCM6 study revised this, and concluded that there was weak correlation with the critical gap parameter. Calibration is now based only on follow-up time, which is now used to adjust the *Y* intercept of the capacity line. The unchanged capacity line is therefore moved either up or down with the adjusted *Y* intercept (*3*).

Assessment of the Form of the HCM Model

The HCM6 model does not relate driver behavior or capacity to roundabout geometry as their findings showed a low correlation between geometry and capacity.

The regression models for the single-lane roundabout sites show the fit to all of the single-lane data with exponential and linear models (Figure 3). Both of them fit equally well based on the root mean squared errors (RMSE). Figure 3 also shows the HCM6 model, which was calibrated to the average follow-up time, that is, the global *Y* intercept anchored at 1,380 pc/h. With this constraint the HCM6 model did not fit the data as well as the other two models. Statistically speaking, it was found that such a constraint was problematic and not well justified.

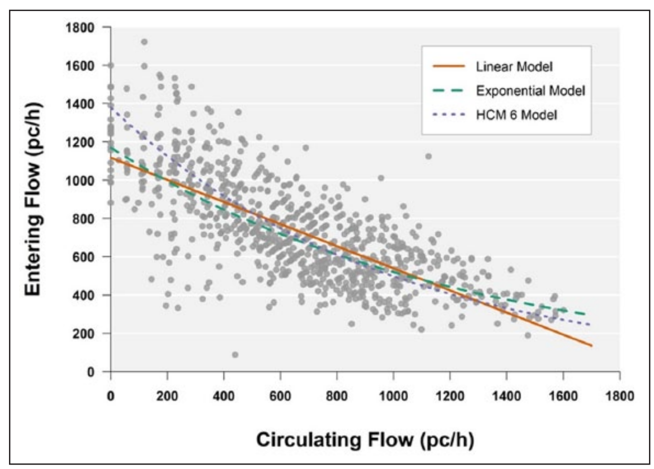
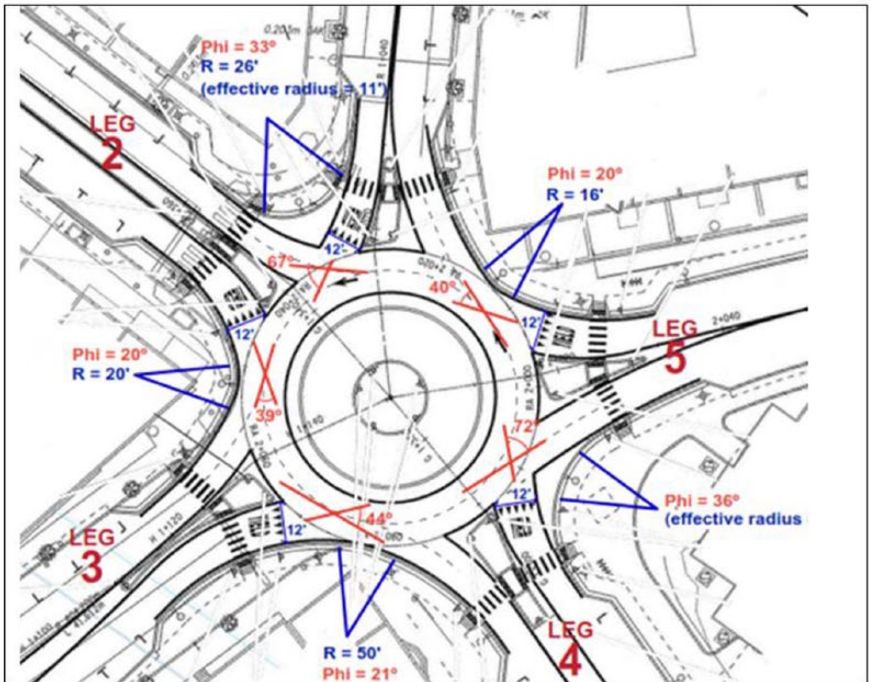


Figure 3. Regression models for single-lane roundabout sites: linear and exponential models fitted directly to the data; HCM6 model calibrated to average follow-up time.

Using regression analysis, fixing the *Y* intercept implies that it is a known value and there is no variation when *X*=0. This implies that there is no variation in capacity when the circulating flow is zero. However, this is not supported by the observed capacity variation at zero circulating flow. By



V	n	E	n	L'	R	Φ	D
11.00	1	12.00	1	20.00	21.00	26.00	105.00

Capacity Output

Y Intercept (vehs/hr)		Slope (tangent)		X Intercept (vehs/hr)	
Entry	Bypass	Entry	Bypass	Entry	Bypass
978		0.4845		2018	

Figure 4. Geometric parameters for Glens Falls, NY-US 9/Warren St./Hudson Ave./Glen St. roundabout.

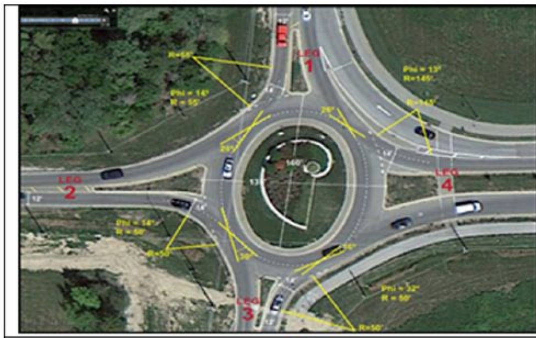
anchoring the *Y* intercept, the HCM6 model ignored these variations and was unable to explain them.

Furthermore, a hypothesis test was performed to determine whether the *Y* intercept equals 1,385 based on the other two models. The calculated intercept of the linear model was found to be 1,117 with a standard error of 13.52, and the estimated intercept of the exponential model is 1,170 with a standard error of 1.02. Both models showed that the "true" intercept is significantly different from 1,385 (both p-values < 0.00001). Therefore, anchoring the *Y* intercept at 1,385 pc/h was not supported by the data or by statistical reasoning. In summary, both the linear and the exponential curves fit equally well to the aggregated single-lane data, and both performed better than the HCM6 anchored model that uses a global average follow-on time of 2.6 s.

Analysis of Data Segregated by Geometry

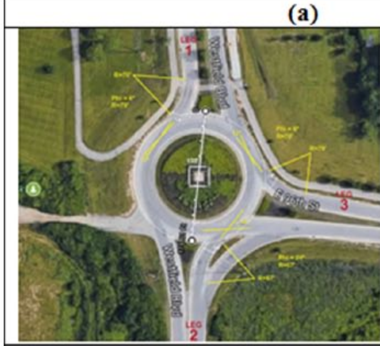
To assess if the geometric model may explain the wide variation in the data, the HCM6 field data were disaggregated into two data sets based on two distinct types of single-lane geometry: the smaller, compact geometry at the Glens Falls, NY, site and the larger, more curvilinear geometry at the five Carmel roundabouts (Figures 4 and 5). The disaggregated data formed two distinct groups with less spread when compared with aggregated HCM6 data.

Kimber's six geometric capacity variables were measured for the two types of roundabouts. As each type has a range of geometry, the six geometric parameters were averaged for each type.

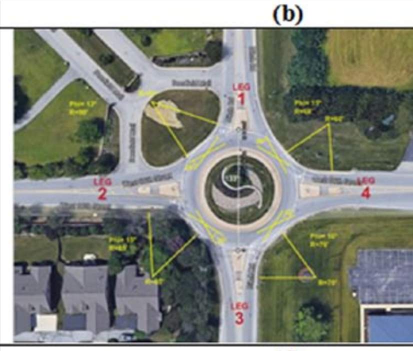


(a)

(b)



(c)



(d)

(e)

Carmel		
	Range	Avg
e’	13-15	14
v	0	12
l'	20-25’	23’
D	130-148’	138
r	55-70	65
Phi ϕ	12-20	16 deg

Geometric Inputs (Averaged for All Entries)

V	n	E	n	L'	R	Φ	D
12.00	1	14.00	1	23.00	65.00	16.00	138.00

Capacity Line Output

Y Intercept (vehs/hr)		Slope (tangent)		X Intercept (vehs/hr)	
Entry	Bypass	Entry	Bypass	Entry	Bypass
1298		0.5783		2244	

Figure 5. Carmel, IN, roundabouts and geometric inputs: (*a*) 116th/Spring Mill Rd., (*b*) 106th/Spring Mill Rd., (*c*) 96th St./Ditch Rd., (*d*) 96th St./Westfield Blvd., and (e) 136th St./Keystone Pkwy.

Smaller Single-Lane Geometrics: NY

The geometric parameters for the NY roundabout and its averaged values are illustrated in Figure 4. These are: approach roadway width (v) = 11’, entry width (e) = 12’, flare length ($l’$) =20’, entry radius (r) = 21’, entry angle (ϕ) = 26°, and diameter (D) = 105’.

Larger, Curvilinear Single-Lane Geometrics: Carmel

The five larger, more curvilinear roundabouts in Carmel, IN, are: 116th St. & Spring Mill Rd., 106th St. & Spring Mill Rd., 96th St. & Ditch Rd., 96th St. & Westfield Blvd., and 136th St. & Keystone Pkwy. (Figure 5).

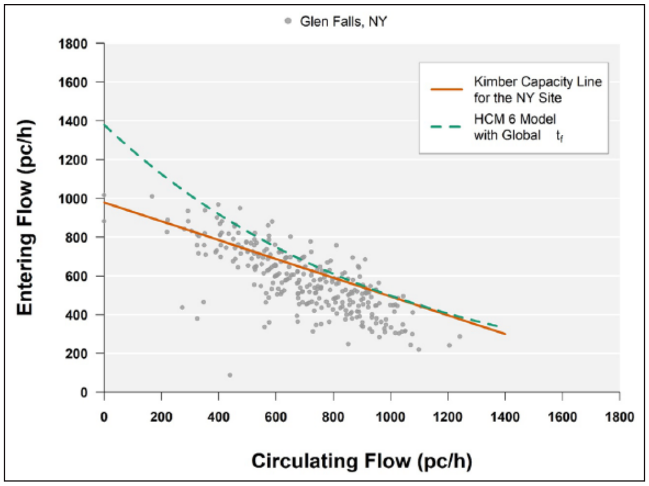


Figure 6. Glens Falls, NY: Uncalibrated Kimber capacity line ($Y = 995 - 0.4695X$) for the NY site compared with uncalibrated HCM6 model with global follow-on time of 2.6 s.

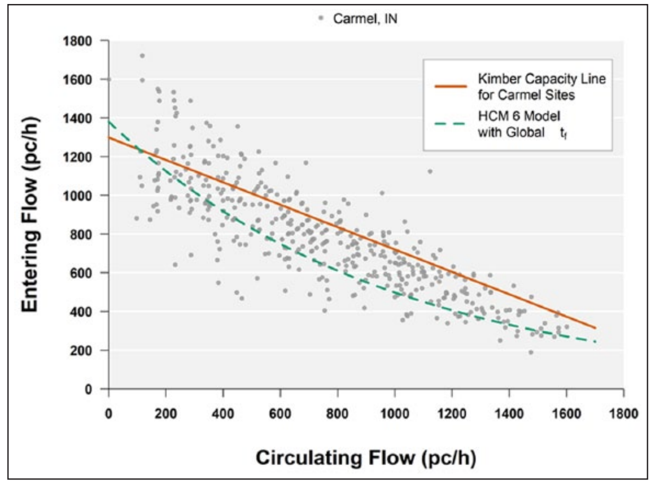


Figure 8. Uncalibrated Kimber capacity line ($Y = 1298 - 0.5783X$) for the Carmel sites compared with HCM6 model uncalibrated with global follow-on time of 2.6 s.

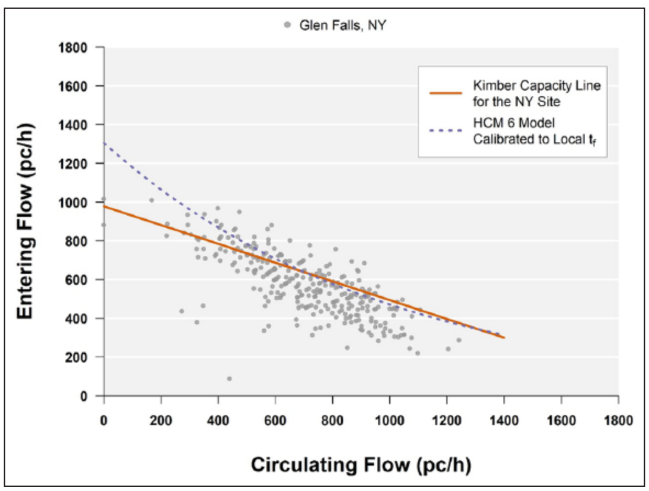


Figure 7. Uncalibrated Kimber capacity line ($Y = 995 - 0.4695X$) for the NY site compared with HCM6 calibrated with local follow-on of 2.8 s.

Figure 5 includes the geometric parameters for each roundabout and their averaged values. These are: approach road width (v) = 12', entry width (e) = 14', flare length (l') = 23', entry radius (r) = 65', entry angle (ϕ) = 16°, and diameter (D) = 138'.

Using the average geometric parameters of each type, the predicted capacity line of Kimber's uncalibrated model was compared with the field-measured data and this was compared with the anchored HCM6 capacity line, calibrated to the local follow-on time.

The RMSE value was derived for each model to assess how closely the predicted capacity line fits the observed data. The model with the lower RMSE is the better fit. (The statistical analysis was performed using R Version 3.2.3). The results of this analysis are discussed in the following sections.

Analysis Results of the Smaller, Compact Geometry: NY Glens Falls Data

Kimber's uncalibrated model used the average geometric parameters to predict the capacity. The capacity line was also predicted by the uncalibrated HCM6 model using the global follow-up time (2.6 s). Both lines were compared with the observed capacity data (Figure 6).

The RMSE values for uncalibrated Kimber and uncalibrated HCM were 112 and 164, respectively. Kimber's geometric model was a better match to the data than HCM6 which overestimated the capacity at low circulating flows. The geometric model's prediction suffers from using averaged geometric parameters. When the actual parameters are used for an entry, the fit to the observed capacity data for that entry is much better.

Kimber's uncalibrated geometric model is compared with the calibrated HCM6 model (2.8 s local follow-on time) with the observed capacity data (Figure 7).

The RMSE for the Kimber uncalibrated model was unchanged at 112, and the RMSE for HCM6 calibrated to the average local follow-up time (2.8 s) was 138. The calibrated HCM6 model had a better fit than the uncalibrated HCM6, but it was not as good as Kimber's uncalibrated model. It also continued to overestimate the capacity at low circulating flow.

Analysis Results of Larger, Curvilinear Geometrics: Carmel Data

Kimber's uncalibrated geometric model is compared with the uncalibrated HCM6 model (2.6 s global follow-on time) with the observed capacity data (Figure 8).

The RMSE for the uncalibrated Kimber model was 172. The uncalibrated and locally calibrated HCM6 models had an RMSE of 183 and 178, respectively. The geometric model

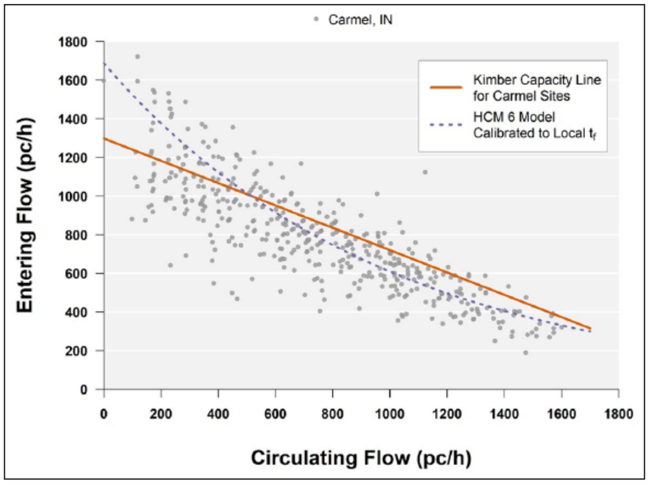


Figure 9. Uncalibrated Kimber capacity line ($Y = 1298 - 0.5783X$) for the Carmel sites compared with HCM6 model calibrated with local follow-on time of 2.13 s.

Table 5. Averaged Data and Geometric Inputs for 106th and 116th at Spring Mill Rd.

Parameter	Range	Average
e	0	14
v	0	12
l’	20–30’	25’
D	140–148’	144
r	55–67	62
ϕ	15–21	19°

performed slightly better than both of the HCM6 models on this segregated data set.

Kimber’s uncalibrated geometric model is compared with the locally calibrated HCM6 model (2.13 s local follow-on time) with the observed capacity data (Figure 9).

The RMSE for the locally calibrated HCM6 model was 178. As noted previously, the geometric model performed slightly better than both of the HCM6 models on this segregated data set.

Further Data Reduction by Geometric Variables

Although the geometric parameters among the five Carmel sites were similar, they still presented a range of geometries. Subsequent evaluation of the data reveals that of the five Carmel sites, 116th at Spring Mill Rd. and 106th at Spring Mill Rd. have less geometric variation though they still include a significant proportion of the Carmel data.

To determine if the geometric model provided a better fit with a narrower geometric range, the capacity data from these two sites were examined. The average geometric parameters for the two Carmel roundabouts are compared with the average of all five sites—the average radius (*r*) decreased, phi angle (*ϕ*) increased, and diameter (*D*) increased (Table 5).

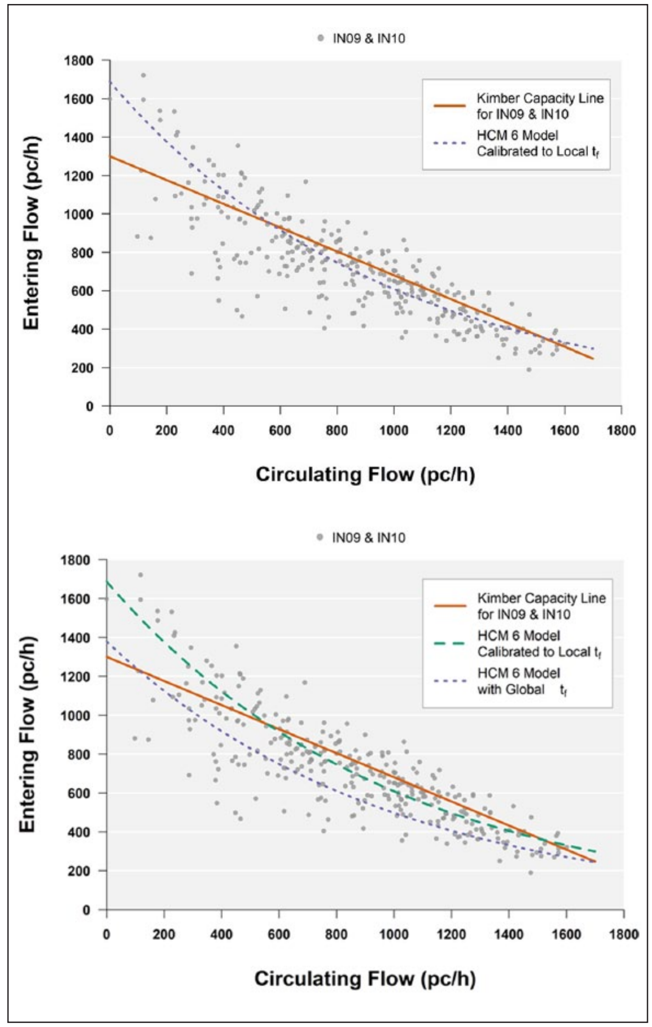


Figure 10. Uncalibrated Kimber capacity line ($Y = 1300 - 0.6198X$) for the two Carmel sites compared with uncalibrated and calibrated HCM6 models (follow-on times of 2.6 s and 2.13 s, respectively).

The uncalibrated Kimber model (using the average geometry of the two sites) is compared with both the uncalibrated and locally calibrated HCM6 models with the observed capacity data from these two roundabouts (Figure 10).

The RMSE for Kimber’s uncalibrated model was 155. The uncalibrated and locally calibrated HCM6 models had an RMSE of 181 and 158, respectively. Kimber’s model performed better with the narrowed geometric parameters than both of the HCM6 models. Narrowing the data from the five Carmel sites to two sites reduced the uncalibrated Kimber RMSE from 172 to 155.

Summary

Kimber’s uncalibrated geometric capacity model gave better predictions than the locally calibrated HCM6 model. Without local calibration the geometric model provided good predictions of capacity at the geometrically distinct Glens Falls, NY, site and the Carmel sites. This implies that the large variation in the data from all sites is caused by geometric variation. The results show that with smaller, more compact roundabouts, the HCM6 model overestimated the entry capacity; with larger, more curvilinear roundabouts, however, it underestimated the entry capacity at mid- to higher-range circulating conditions and overpredicted capacity at lower circulating flows.

The HCM6 model with local calibration performed better. However, it is noted that the analysis used local follow-on times for roundabouts with distinct geometries. This suggests that the differences in geometry are a significant cause of the different follow-on times for each location. This was reinforced by the results from the uncalibrated geometric model. It is therefore concluded that the difference in driver behavior, manifested by the difference in follow-on times at each site, is caused primarily by the differences in geometry.

Conclusion and Future Research

This paper examined the single-lane capacity data collected in 2012 for existing saturated single-lane US roundabouts as part of the FHWA project, Assessment of Roundabout Capacity Models for the Highway Capacity Manual. These data were used to update HCM 2010 to HCM6.

The wide range of single-lane data is problematic for accurate capacity prediction. This wide scatter suggests that there may be geometric distinctions between single-lane roundabouts that affect their capacity. To examine this hypothesis, the data were segregated into two geometrically distinct types of roundabouts—smaller, compact geometrics and larger, curvilinear geometrics. The data points for each type of single-lane roundabout were distinct and had less scatter than the aggregated data of all the single-lane roundabouts.

To further examine if these differences in capacity were caused by the differences in geometry, Kimber's uncalibrated geometric model was used to predict the capacity line using the geometry of each type. This gave a good fit to both sets of data, reinforcing the hypothesis that the capacity variation is explained by the difference in geometry.

The HCM6 model relies on local follow-on times to account for differences in driver behavior. However, Kimber's geometric model relates capacity directly to geometry. The good fit between the uncalibrated geometric model and the local data indicates that the geometric differences between sites are the primary cause of the difference in driver behavior between sites.

These findings could be further tested by selecting geometrically opposite roundabouts for each of the two regions (a larger, more curvilinear roundabout in New York, and a smaller, more compact single-lane roundabout in Indiana). If the results support those of this paper, it would confirm that the differences in driver behavior are caused primarily by differences in geometry rather than "regional" nongeometric driver behavior. Roundabouts in the same area with markedly different geometries would also be a useful test, as the regional follow-on time would be the same for both, but the actual times quite different because of their geometric differences.

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