Operational Performance of a Double-Lane Roundabout with Additional Lane Length Design: Lighthill-Whitham-Richards Model Analysis

Samuel Hammond, Anaïs Rat, Maria Laura Delle Monache, Benedetto Piccoli

Operational Performance of a Double-Lane Roundabout with Additional Lane Length Design: Lighthill-Whitham-Richards Model Analysis

Samuel Hammond
Assistant Professor
Rowan University
Glassboro, NJ
Email: hammonds@rowan.edu

Anaïs Rat
Graduate Research Assistant
Rutgers University
Camden, NJ
Email: anais.rat@gmail.com

Maria Laura Delle Monache
Univ. Grenoble Alpes, Inria, CNRS, Grenoble INP*, GIPSA-Lab, 38000 Grenoble, France
* Institute of Engineering Univ. Grenoble Alpes
Email: ml.dellemonache@inria.fr

Benedetto Piccoli
Associate Provost for Research
Rutgers University
Camden, NJ
Email: b.piccoli@gmail.com

ABSTRACT

There is a general notion among transportation professionals that having a longer additional lane length at a double-lane roundabout entry yields better performances. This paper investigates this notion using Lighthill-Whitham-Richards Model Analysis. Using Lighthill-Whitham-Richards model, a double-lane roundabout with additional lane design at the entry is analyzed. The additional lane lengths are varied at the entry in order to study the effect of different additional lane lengths on roundabout performance. A scalar hyperbolic partial differential equation (PDE) model for traffic velocity evolution based on the seminal Lighthill-Whitham-Richards (LWR) PDE for density is used. Equivalence of the solution of the velocity PDE and the solution of the LWR PDE is shown for quadratic flow rate functions. The results were then compared with similar lane length variations in VISSIM. The findings from this study are intended to provide transportation professionals with the ability to assess the effects of geometric design changes on operational performance. From the analysis presented in this paper, the delay and speed can be predicted from knowledge of the geometric parameters. While the design of an additional lane differs from a flared entry, findings from this study can also be applied to flare lengths if they are designed to operate in a similar fashion as additional lane entry used in this study.

Keywords: roundabout operation, additional lane length, flare length, Lighthill-Whitham-Richards, Riemann solver, scalar conservation laws

INTRODUCTION

The roundabout has emerged as a popular form of intersection control in the United States due to its effectiveness in improving safety and reducing traffic congestion. However, there has not been much research performed domestically that addresses how different geometric parameters quantitatively affect performance. Hence, most transportation professionals refer to studies conducted overseas that do not necessarily translate directly to domestic roundabout design and operation.

To date, roundabout capacity models developed in the US are based on gap acceptance theory which does not completely help practitioners with design because it does not provide any direct relationship between geometric parameters and performance. In practice, a traffic engineer needs to know the relationship between the geometric parameters and capacity in order to design roundabouts to accommodate specific traffic volumes. Driver behavior which is used in gap acceptance models is difficult to predict especially by transportation professionals.

A macroscopic model that accounts for the roundabout geometric parameters is used in this study. The origins of macroscopic traffic flow models date back to 1950's, when the seminal works of Lighthill and Whitham and Richards (LWR) proposed a fluid dynamic model for vehicular traffic flow on an infinite single road. First-order scalar conservation law models of the LWR type have been widely used in the traffic science and engineering literature, due to its relatively simple mathematical structure and the capability of capturing realistic traffic network phenomena such as shock waves and vehicle spillback.

This paper examines the effect of varying additional lane lengths on roundabout operation. In this paper, a double-lane roundabout with an inscribed circle diameter of 180 feet and four approaches aligned at 90 degrees is be modeled as a concatenation of junctions. At each junction, the Riemann problem is solved using a right of way parameter, and solutions are constructed exactly via wave-front tracking method. The wave-front tracking method consists of approximating the exact solution by piecewise constant, both in time and space, functions. More precisely, the time-varying Riemann solvers are also approximated by means of piecewise constant (in time) Riemann solvers. Work in this regard includes Garavello and Piccoli (2), Bressan (3) and Coclite et al. (4) which illustrate Riemann solvers for Traffic Flow at a junction.

Delay and speed are the cost functionals that were considered at specified locations on the roundabout. The delay and speed data obtained from this model were compared with that of a microscopic model developed in VISSIM.

METHODOLOGY

This section details how the research effort was conducted with respect to modeling the impact of additional lane length on roundabout operation. In the flare design, a single lane is gradually widened into two lanes at the entry (see Figure 1). In the additional lane length design, a full lane is added at the entry and a taper of sufficient length is provided. Both design cases result in the widening of the entry and increases the rate that vehicles enter the roundabout at a given time. This means that in terms of operation a single traffic stream separates into two streams for both the additional and flare design. The additional lane design was used in this research to examine the effect on a roundabout; the findings applied to flared entry as well.

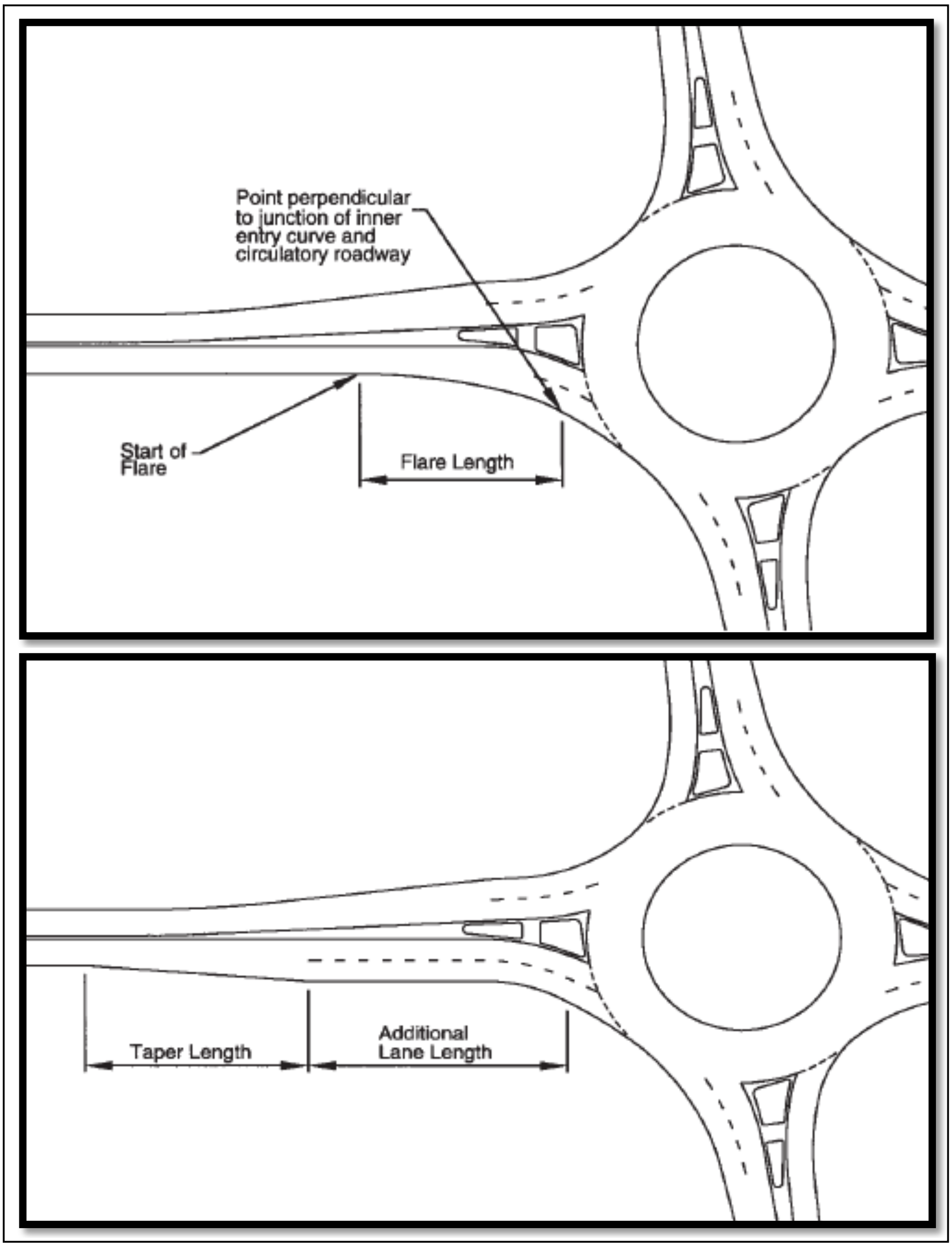


FIGURE 1 Flaring and Additional Lane Design (Source: FHWA Roundabout Guide)

The hypothetical roundabout design developed by Hammond et al. (5) was used. The roundabout design involved a double-lane roundabout (Figure 2) with four legs aligned at 90 degrees and an inscribed circle of 180 feet was used for this study. Lane width of 16 feet was considered.

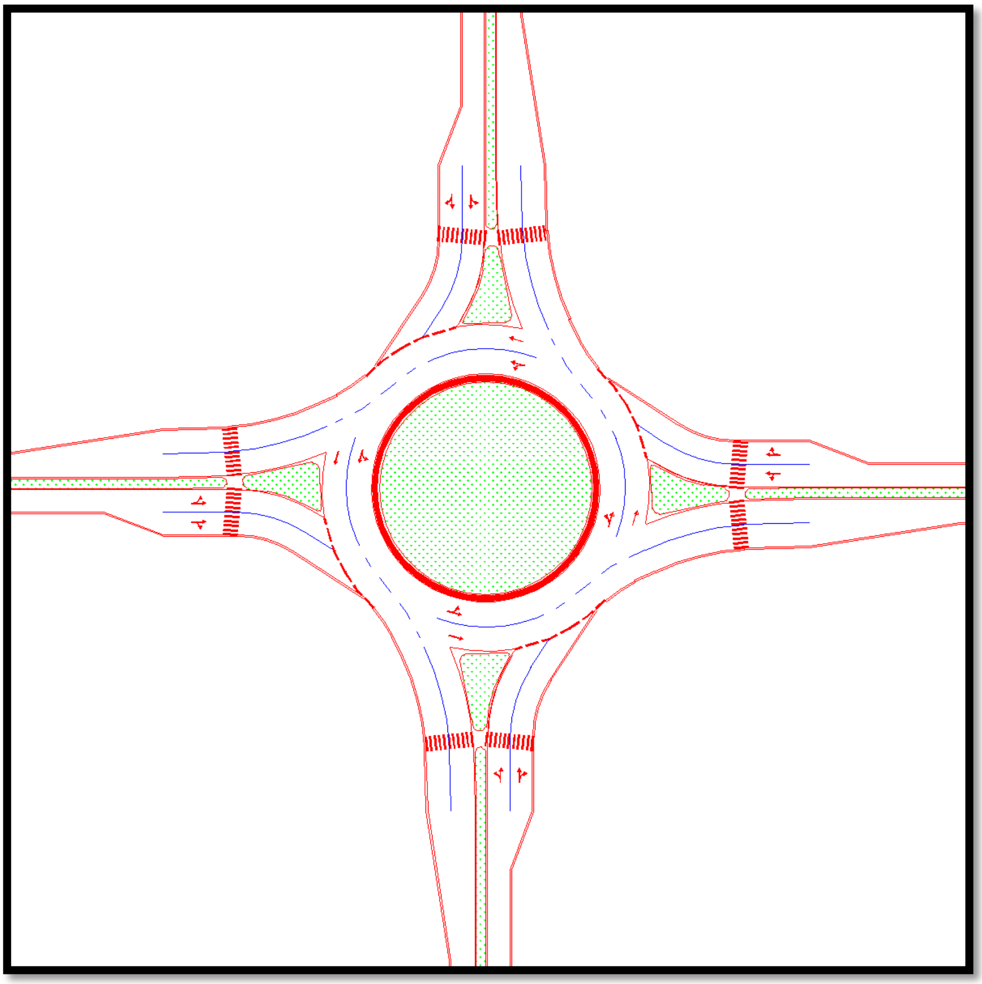


FIGURE 2 Roundabout Design

A degree of saturation less than 0.80 was targeted based on the following assumptions:

- The major road was established in the north-south direction with a volume of 800 vehicles per hour in each direction
- The minor road was established in the east-west direction with a volume of 350 vehicles per hour in each direction
- The right lane was assumed to be the critical lane in all directions
- Fifteen percent of the volume consisted of heavy vehicles

Starting with an additional lane length of 50 feet the operational performance of the roundabout was analyzed. Table 1 shows the different scenarios used for the model analysis:

- Scenario 1: Only the entry additional lane length was varied while the exit additional lane length was kept at 50 feet.
- Scenario 2: Both entry and exit additional lane length were varied.

TABLE 1 Model Scenarios

	Scenario 1								Scenario 2							
Additional Lane	East		West		South		North		East		West		South		North	
Location	Entry	Exit	Entry	Exit	Entry	Exit	Entry	Exit	Entry	Exit	Entry	Exit	Entry	Exit	Entry	Exit
Variation 1	X		X		X		X		X	X	X	X	X	X	X	X
Variation 2					X								X	X		
Variation 3			X								X	X				

Under Scenario 1, three variations were considered:

1. Additional lane lengths at the entry of all four legs were varied at the same time. This scenario was represented by HA in this study, where H represents the hypothetical design and A represents all legs.
2. An additional lane at the entry with the highest volume (south leg) was varied. This scenario was represented by HS, where H represents the hypothetical design and S represents the south leg.
3. An additional lane at the entry with the lowest volume (west leg) was varied. This scenario was represented by HW, where H represents the hypothetical design and W represents the west leg.

Under Scenario 2, three variations were considered:

1. Additional lane lengths at the entry and exit of all four legs were varied at the same time. This scenario was represented by HAX in this study, where H represents the hypothetical design, A represents all legs, and X represents the exit.
2. An additional lane at the entry and exit with the highest volume (south leg) was varied at the same time. This scenario was represented by HSX, where H represents the hypothetical design, S represents the south leg, and X represents the exit.
3. Only one additional lane at the entry and exit with the lowest volume (west leg) was varied at the same time. This scenario was represented by HWX, where H represents the hypothetical design, W represents the west leg, and X represents the exit.

The additional lane lengths that were analyzed in for both scenarios included: 50 feet, 150 feet, 250 feet, 350 feet, 450 feet and 550 feet.

MACROSCOPIC MODEL

The double-lane roundabout was modeled as a network with 52 links and 28 junctions as shown in Figure 3.

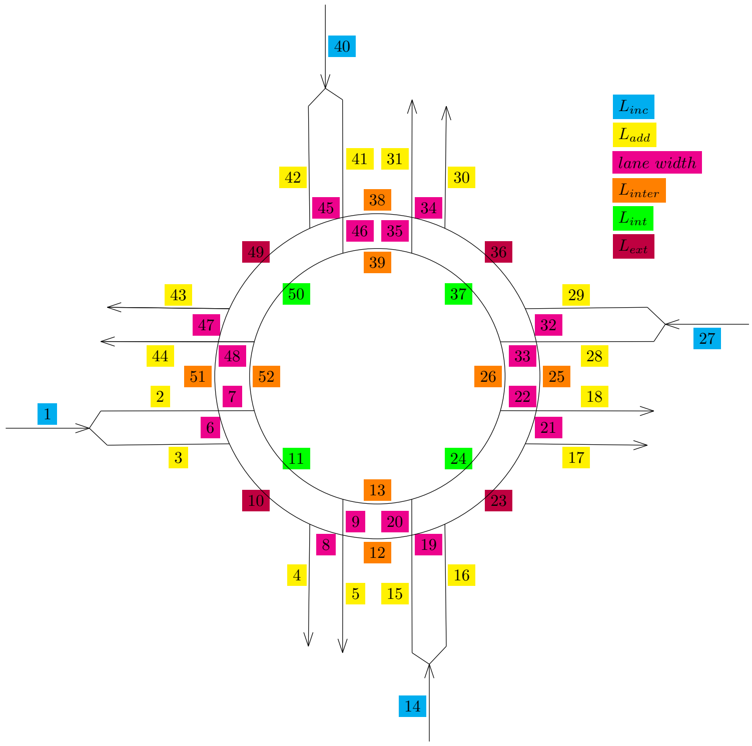


Figure 3 Roundabout Network Links

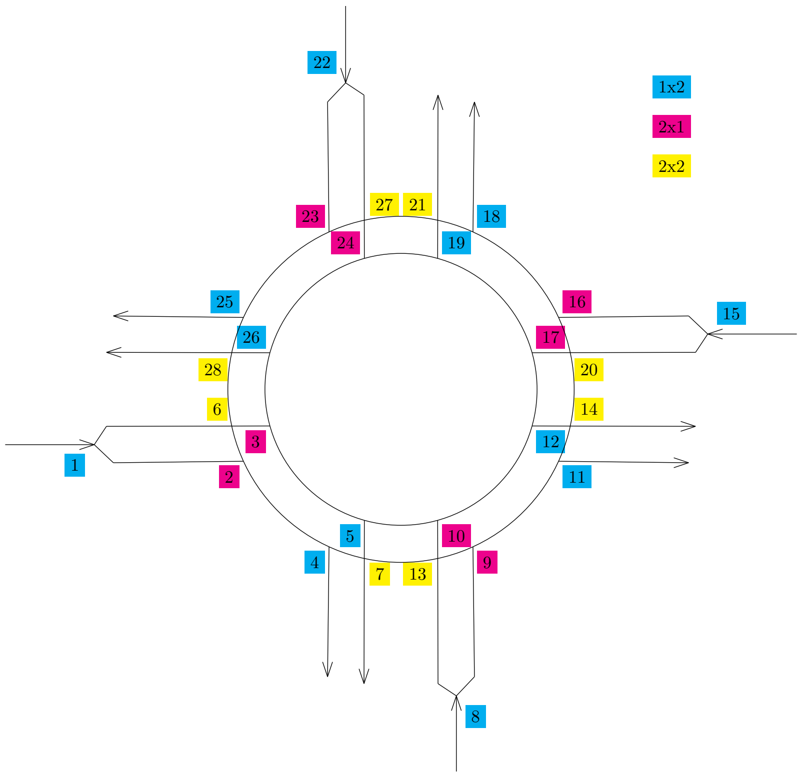


Figure 4 Roundabout Network Junctions

Each road considered had a single scalar conservation law defined on edges modeled by intervals $[0, L_i]$ for $i \in (1, \dots, 52)$. The traffic evolution was then described by the LWR model. In particular, the traffic density evolution was mathematically described by the following partial differential equation (PDE):

$$\partial_t \rho_i + \partial_x f(\rho_i) = 0, \qquad (x, t) \in [0, L_i] \times \mathbb{R}^+ \quad \forall\, i \in [1, \dots, 52]$$

where $\rho_i(x, t)$ is the car density along the road i and $f(\rho_i)$ is the flux (also referred to as flow rate) function. Denoting v_{max} as the maximal speed and $\rho_{max,i}$ as the maximal capacity (Figure 5) of each link then:

$$f(\rho_i) = v_{max}\rho\left(1 - \frac{\rho_i}{\rho_{max,i}}\right) \quad \forall\, i \in [1, \dots, 52]$$

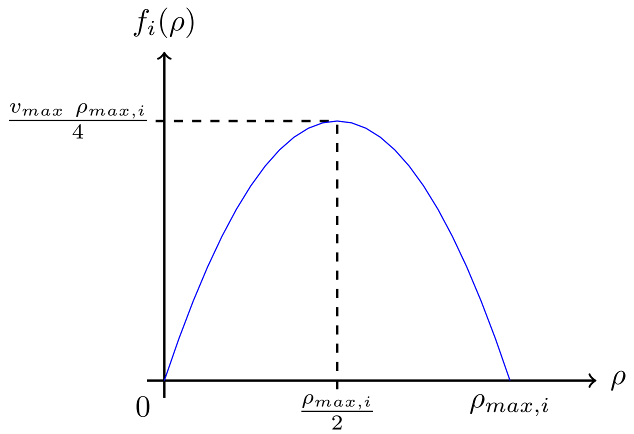


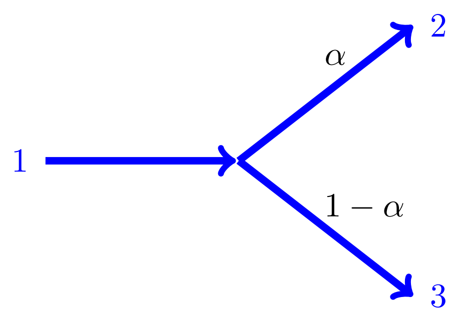
Figure 5 Fundamental Flux Function

Each junction was modeled according to the following rules:

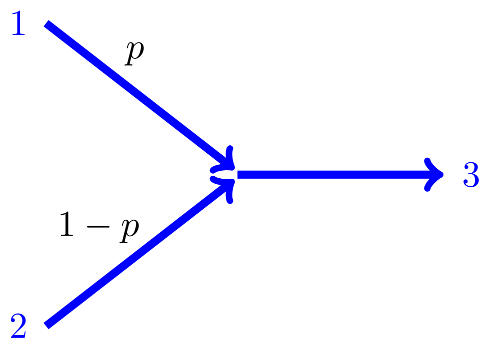
1. The flux through the junction should be maximized
2. The traffic at the junction should be distributed following a traffic distribution matrix A and priority parameters p, q when needed.

The three different types of junctions considered are:

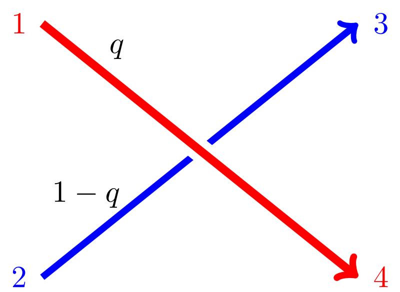
1. Diverging junction



2. Merging Junction



3. Crossing junction



DIVERGING JUNCTIONS 1X2

Letting $\alpha_j \in [0,1]$ represent the split ratio among the link 1 and link 2 for a junction j, and $\gamma_{1,j}, \gamma_{2,j}$ and $\gamma_{3,j}$ represent the fluxes on each one of the single links, the traffic distribution matrix can then be defined as $A_j = (\alpha_j, 1-\alpha_j)^T$. The fluxes on each link can be computed as:

$$\hat{\gamma}_{1,j} = \min\left(\gamma_{1,j}, \frac{\gamma_{2,j}}{\alpha_j}, \frac{\gamma_{3,j}}{1-\alpha_j}\right).$$

$$\hat{\gamma}_{2,j} = \alpha_j \Gamma_j$$

$$\hat{\gamma}_{3,j} = (1-\alpha_j)\Gamma_j$$

respectively for link 1, 2 and 3.

MERGING JUNCTIONS 2X1

Introducing the priority parameter $p_j = 0.804$ for a junction j which defines the right of way of the link 1, the flux on each single link can be given by:

$$\hat{\gamma}_{3,j} = \min(\gamma_{1,j} + \gamma_{2,j}, \gamma_{3,j})$$

$$\hat{\gamma}_{1,j} = \min[\gamma_{1,j}, \max(\hat{\gamma}_{3,j} - \gamma_{2,j}, p\,\hat{\gamma}_{3,j})]$$

$$\hat{\gamma}_{2,j} = \hat{\gamma}_{3,j_j} - \hat{\gamma}_{1,j}$$

CROSSING JUNCTIONS 2X2

Letting Γ_j^{max} represent the capacity of the crossing junction j, which is defined as the maximum capacity of the link of the junction. Then, denoting $\gamma_{1\to 4,j}^{max} = \min(\gamma_{1,j}, \gamma_{4,j})$ and $\gamma_{2\to 3,j}^{max} = \min(\gamma_{2,j}, \gamma_{3,j})$ as the maximum admissible fluxes respectively on the axes $1 \to 4$ and $2 \to 3$ when they do not cross.

Two cases can be considered:

(1) $\gamma_{1\to 4,j}^{max} + \gamma_{2\to 3,j}^{max} \leq \Gamma_j^{max}$ (that is, if the fluxes on each axes can be maximized without exceeding the capacity of the junction): then

$$\Gamma_j = \gamma_{1\to 4,j}^{max} + \gamma_{2\to 3,j}^{max} \quad \text{and} \quad \hat{\gamma}_{1,j} = \hat{\gamma}_{4,j} = \gamma_{1\to 4,j}^{max}, \quad \hat{\gamma}_{2,j} = \hat{\gamma}_{3,j} = \gamma_{2\to 3,j}^{max}$$

(2) otherwise, $\Gamma_j = \Gamma_j^{max} = \hat{\gamma}_{1\to 4,j} + \hat{\gamma}_{2\to 3,j}$
where $\hat{\gamma}_{1\to 4,j}$ and $\hat{\gamma}_{1\to 4,j}$ can be determined the same way as $\hat{\gamma}_{1,j}$ and $\hat{\gamma}_{2,j}$ for the 2×1 junction replacing p by q, the index 1 by $1 \to 4$, and 2 by $2 \to 3$:

$$\begin{cases} \hat{\gamma}_{1\to 4,j} = \min[\ \gamma_{1\to 4,j}^{max}, \max(\ \Gamma_j - \gamma_{2\to 3,j}^{max}, q\,\Gamma_j)\ ] \\ \hat{\gamma}_{2\to 3,j} = \Gamma_j - \hat{\gamma}_{1\to 4,j} \end{cases}$$

Finally, $\hat{\gamma}_{1,j} = \hat{\gamma}_{4,j} = \hat{\gamma}_{1\to 4,j}$ and $\hat{\gamma}_{2,j} = \hat{\gamma}_{3,j} = \hat{\gamma}_{2\to 3,j}$.

The traffic flow on the links in the network was then simulated in a time interval [0, T], where T = 5 hours. For the initial condition on the links in the network, it was assumed the initial time t = 0 on all the links were empty, and we assume a demand function of the 800 vehicles per hour for the direction north-south and 350 vehicles per hours in the direction east-west.

MICROSCOPIC MODEL

In practice, some use microscopic models for design, so in an attempt answer the question of whether one would obtain similar results from a microscopic model, the microscopic model developed by Hammond et al. (5) was used for comparison. The roundabout design used in the microscopic model had the same geometric parameters as the macroscopic model used in this research. The model was developed in VISSIM and the lengths varied under similar scenarios. The only difference is the microscopic model length variation started at 0 feet as opposed to 50 feet used in the macroscopic model.

RESULTS AND DISCUSSION

The delay and speed data for the macroscopic model are shown in Figure 5. The delay data represent the difference between the measured travel time and free flow travel time from a location of 250 feet approaching the yield line on the entry leg to the exit point on the circulatory roadway. Figure 5 also shows the average speed between these two locations. Data from the macroscopic model show that the highest delay occurred when the model had shorter lengths for each scenario. There was no significant difference between scenarios 1 and 2. There was no significant decrease in delay for the various lengths. In general, an increase in lane length resulted in an increase in vehicle speed. The microscopic model (Figure 6) also showed similar results beyond the 50 feet length; there was not significant change in delay as the lengths were increased. The speed for the microscopic model also increased with increasing length.

As the speed data shows, increasing the lengths caused the speed to increase at the entries; this decreased the time required for vehicles to reach the circulatory roadway. When additional vehicles reach the circulatory roadway within short period of time the conflicting flow increases and reduces the likelihood of finding an acceptable gap. It is for this reason that the delay increases even though approach speeds are increasing. Increasing the length on just one leg reduced the delay for that entry, but resulted in more vehicles in the circulatory roadway and increased the conflicting flow for other entries. Increasing the length on the entry with the lowest volume (minor road) increased the conflicting flow and caused delay on the major road. The delay on the minor road, which had minimum effect on the intersection, was decreased but the delay on the major road increased, resulting in a slightly increased delay at the intersection overall.

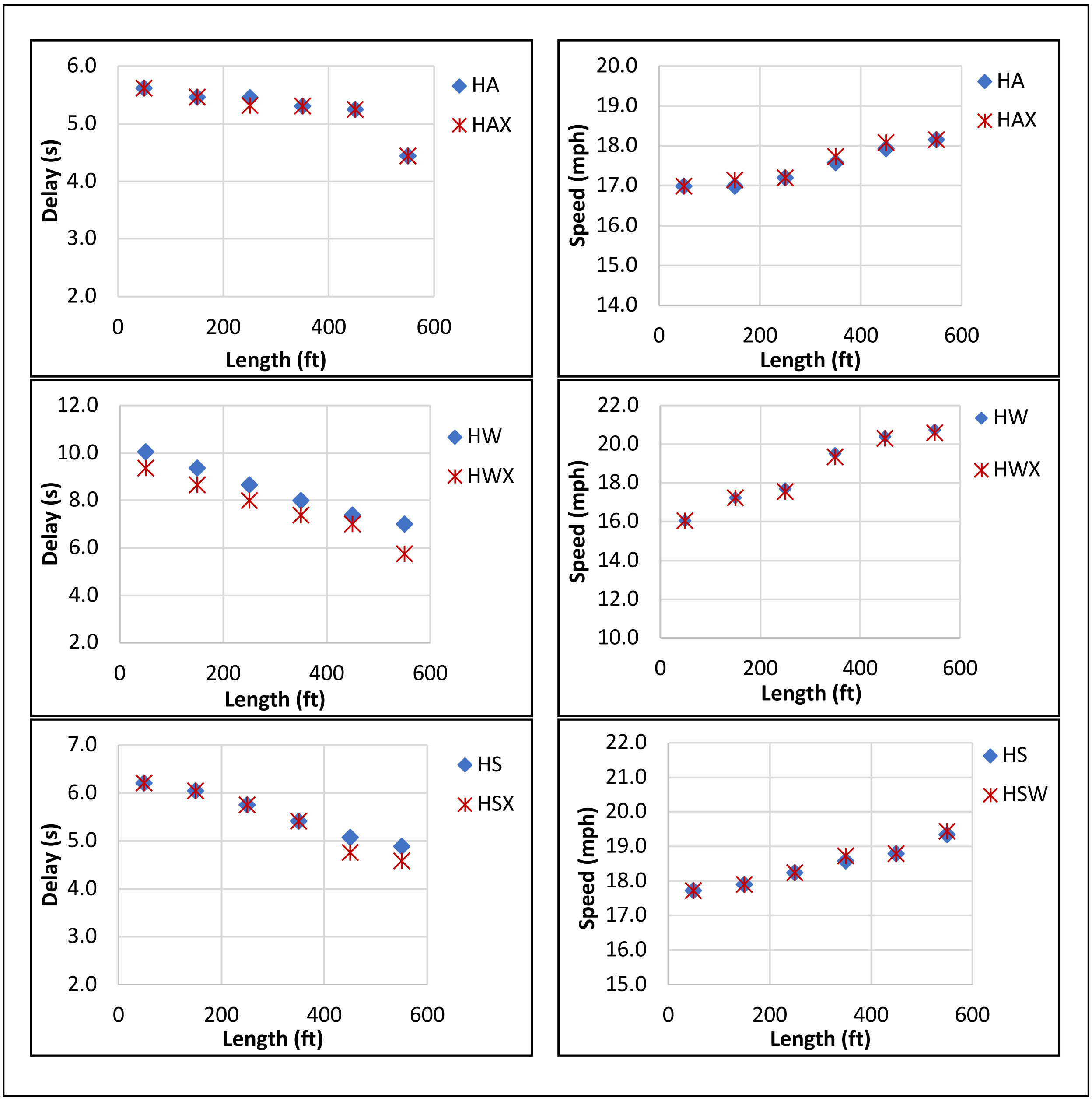


FIGURE 6 Delay & Speed Data for Macroscopic Model

Increasing the length on the entry with the highest volume was more effective than increasing the length on the entry with the lowest volume since the delay on the major road, which significantly contributes to the delay of the entire intersection, was reduced. Increasing the length of just one entry (either highest or lowest volume) was not as effective as increasing all four legs at the same time, as increasing the length on all four legs reduced the delay on each approach, and thus reduced the overall delay of the intersection.

Wu (6) suggested balancing the exit and entry capacities so that the potential of widened entry could be achieved and bottleneck effects at the exit could be avoided. Based on this analysis, the double-lane exit did not affect delay at the intersection. This could be due to the fact that low volumes (or v/c ratios) were considered.

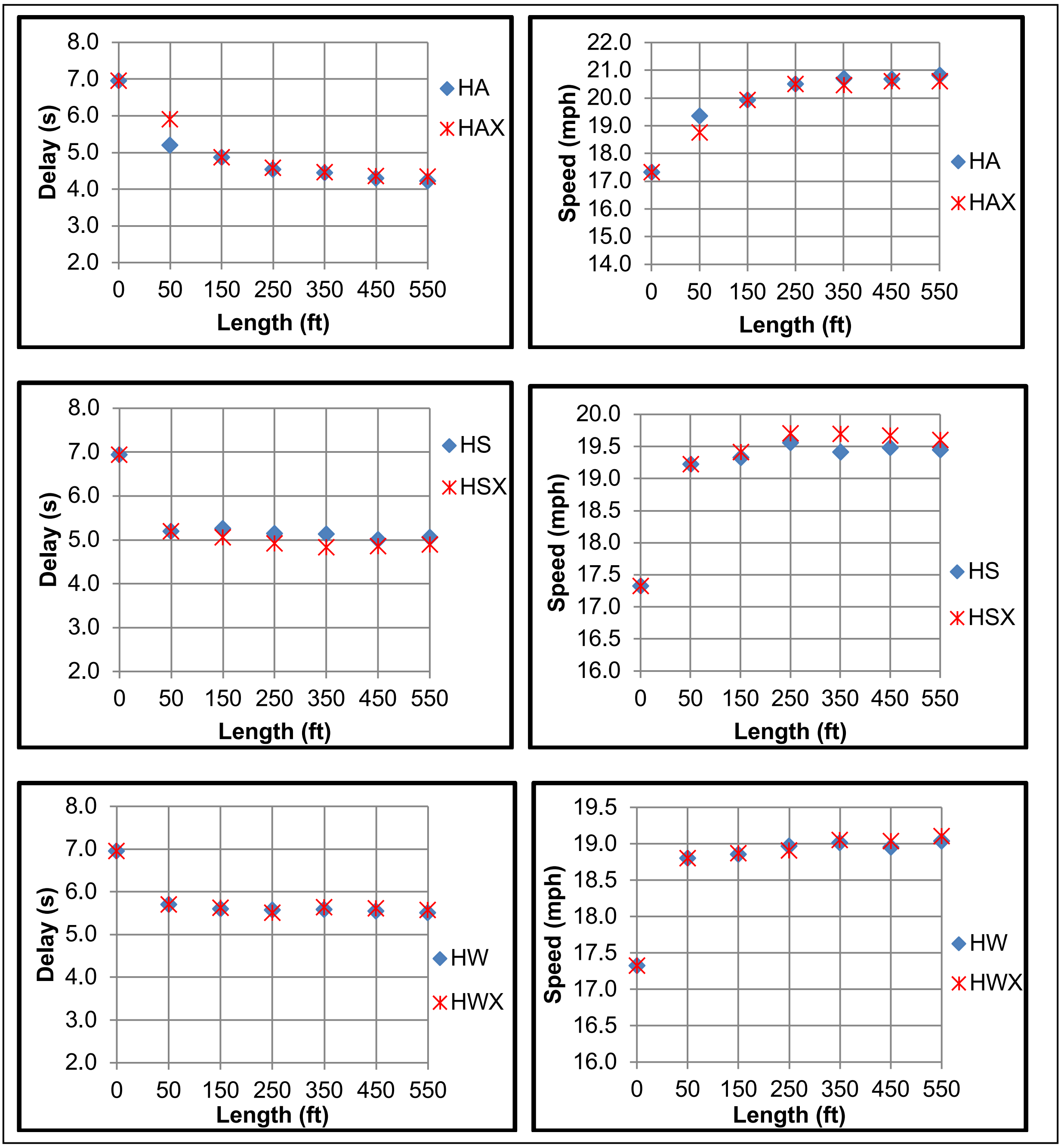


FIGURE 7 Delay & Speed Data for Microscopic Model

CONCLUSION AND RECOMMENDATIONS

The findings from this study are based on double-lane roundabouts with varying approach geometries and additional lane length configurations. The delay values reported in this study were measured from a distance of 250 feet from the yield line on the approach to the point where the vehicle exited the circulatory roadway. Delays upstream of the 250 foot mark and beyond the exit line were not recorded, though delays beyond these limits could add to the magnitude of the data reported in this study. Understanding delay variability within this short interval under the assumed conditions further the body of knowledge with regard to roundabout operations that was initially presented in NCHRP 572 (*7)*.

The analyses of the macroscopic and microscopic roundabout models for lengths beyond 50 feet indicate that very long additional lane lengths were not effective in reducing delay at roundabouts. There was approximately 2-second change in delay over a 500-foot length. This finding corroborates with results from the U.K. Department of Transport Design Manual (8) which recommended shorter flare lengths of about 82 feet to effectively increase capacity and pointed out that longer flare lengths resulted in higher speeds. The findings from this study can also be applied to flare designs. Where flaring is used, additional analysis is needed if the flaring does not result in two entry lanes. At entries where two full lanes are used, longer lengths will result in increased speed and reduced delay.

From an operations standpoint, shorter additional lane lengths between 50 and 150 feet at both the entry and exit were most effective. While adjusting the lane length of all legs was determined to be more beneficial than only adjusting one leg, at a location where only one leg can be modified, the leg with the most volume should be adjusted and length variation should be within the 50 to 150 foot range. If lengths of 150 feet already exist, other modification techniques need be applied as longer lengths will be ineffective in reducing delay. Increasing the lane length allowed vehicles to reach the circulatory roadway faster, but with more vehicles entering the roundabout, the likelihood for conflicting flow increased as well. The NCHRP (7) identifies design procedures that balance entry, circulatory and exit flow through lane numbers and arrangements. Shorter lengths help regulate the rate of entry at a slow but constant rate when compared with longer lengths can result in an instantaneous increase in circulatory roadway flow with less capacity to handle the flow.

The findings from this study will help transportation professionals with regard to roundabout design and operations. This study confirms that longer additional lane lengths are not necessary. It shows that additional lane length can be varied in a manner that effectively reduces delay while avoiding unnecessary lane design and construction; this study can also be used during the planning and design stages of a new roundabout in order to determine the appropriate additional lane length. Additional analysis is needed to determine the effect of different lengths on safety since this study has shown that increasing the lane length can increase the approach speed at a roundabout, and this trade-off could undermine the operational benefits of a modern roundabout facility.

REFERENCES

1. Lighthill, M. J., and Whitham, G. B. (1955). “On kinematic waves II. A theory of traffic flow on long crowded roads.” Proc. Royal Soc. London Ser. A., vol. 229, pp. 317-346.

2. Garavello, M. and Piccoli, B. (2009). Time-varying Riemann solvers for conservation laws on networks Journal of Differential Equations, 247, 447-464.

3. Bressan A. (2000). Hyperbolic systems of conservation laws. The one-dimensional Cauchy problem. Oxford University Press.

4. Coclite, G., Garavello, M., and Piccoli, B. (2005). Traffic flow on a road network, SIAM J. Math. Anal. 36 (6), 1862-1886.

5. Hammond, S., Hunter, C., and Cheng K. (2014). The Effect of Additional Lane Length on Double-Lane Roundabout Operation. Journal of Transportation of the Institute of Transportation Engineers, Vol. 6, Number 1, Institute of Transportation Engineers, Washington, D.C.

6. Wu, N. (1997). Capacity of shared/short lanes at unsignalized intersections. In Proc., Third International Symposium on Intersections without Traffic Signals (M. Kyte, ed.), Portland Oregon, U.S.A., University of Idaho.

7. NCHRP Report 672 (2010). National Cooperative Highway Research Program: “Roundabouts: An Informational Guide.” Second Edition. *Transportation Research Board*, Washington, D.C

8. Kimber, R.M. (1980). *The traffic capacity of roundabouts*. TRRL Laboratory Report LR 942. Transport and Road Research Laboratory, Crowthorne, England.