Operational Evaluation of Two-Lane Roundabouts at Freeway Ramp Terminals

Comparison Between Roundabout and Signalized Interchanges

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In the United States, roundabouts have recently been constructed to replace signalized intersections at freeway ramp terminals as both a safety and an operational treatment. In practice, this treatment is in need of guidelines specifying conditions when the roundabout or signalized intersection is more appropriate to assist practitioners in deciding which alternative to choose. In particular, research providing a comprehensive operational comparison between roundabouts and signalized interchanges is lacking. The current research—though a strictly calibrated microscopic simulation platform—analyzes and models the control delay at double-lane roundabouts and signalized interchanges. Both roundabouts and signalized interchanges were modeled in a Vissim simulation platform. Capacity at each roundabout entrance was calibrated and validated separately for passenger cars and heavy vehicles, since both vehicle types have different critical and follow-up headways. The design of the simulation experiments covered 2,880 different scenarios for roundabouts and signalized interchanges with varying ramp and arterial volumes, ramp spacing, and heavy-vehicle percentages. From the simulation results, control delay and level of service of the off-ramp and arterial approaches of roundabouts and signalized diamond interchanges were modeled and compared. Ultimately, guidelines for the selection between double-lane roundabouts and signalized interchanges were developed and presented in the form of look-up tables. These tables provide an easy-to-use tool for practitioners to determine the appropriate double-lane interchange to install under specific combinations of traffic demand, heavy-vehicle percentage, and ramp spacing conditions.

In the United States, roundabouts have recently been constructed to replace traditional signalized intersections at freeway ramp terminals as both a safety and an operational treatment. For example, in Wisconsin, many roundabouts are in use at freeway ramp terminals. Generally, the double-lane roundabout interchange is considered workable if the sum of the entering plus the circulating traffic at each entry point is between 1,000 vph and 1,300 vph (*1*). In practice, these numbers may not be exactly correct under various combinations of off-ramp and arterial volumes, as well as different ramp spacing and heavy-vehicle percentages. In particular, the effect of heavy vehicles on roundabout capacity is outstanding. Research shows that the critical headway for heavy vehicles is significantly greater than that for passenger cars (*2*); this difference can result in reduced roundabout entrance capacity. The operational impact on roundabout interchanges is obvious with increasing truck traffic at off-ramp and arterial entrances; this effect could increase the entrance delay substantially at roundabout ramp terminals.

These aforementioned issues pertaining to roundabout interchanges do not necessarily apply to signalized diamond interchanges. At signalized interchanges, the operational effect of the heavy-vehicle percentages is less obvious. In addition to heavy vehicles, the operational effects of ramp spacing and traffic demand may be different at a roundabout interchange than at a signalized diamond interchange. Therefore, guidelines are needed to assist decision makers in choosing between roundabouts and signalized intersections when freeway ramp terminals are designed. In practice, there is a lack of such guidelines specifying conditions under which the roundabouts or the signalized intersections are more appropriate at freeway ramp terminals. Little literature was found that documents a comprehensive operational comparison between roundabouts and signalized interchanges.

This study is aimed at quantitatively comparing the operational performance of double-lane roundabout interchanges and signalized diamond interchanges under various conditions of traffic demand, ramp spacing, and heavy-vehicle percentage. As a result of the comparison, guidelines are to be developed that identify suitable conditions for installing a double-lane roundabout interchange versus a signalized interchange. Traditional deterministic methods—such as the *Highway Capacity Manual* (HCM) approaches for capacity and delay analysis—are not sufficient to address traffic dynamics involved in various scenarios (*3*). Also, control delay measurement for interchanges is specified for each origin–destination (O-D) movement that traverses two intersections of the interchange; this situation is not directly addressed by the HCM methods. Moreover, the effect of spacing between the roundabouts at the ramp terminals is not considered in the HCM either. To address these concerns, the comparison is to be conducted via a strictly calibrated and validated microsimulation platform, which can well represent the real-world stochastic traffic operations at roundabouts at ramp terminals. Specifically, the research is carried out with the following objectives:

- To model the stochastic control delay at double-lane roundabouts at ramp terminals;

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• To compare the control delay of the roundabout and signalized interchange with consideration of varying traffic volume, heavy-vehicle, and ramp spacing conditions; and
• To develop guidelines for choosing between double-lane roundabouts and signalized interchanges.

LITERATURE REVIEW

There is little related work that directly and quantitatively compares the operational performance of roundabouts and signalized interchanges. However, previous research did include some discussion about alternative interchange selection from a qualitative perspective. For example, Leisch reported that volumes and patterns of existing and future traffic should be considered when a choice is made between alternative interchange designs (*4*). A Texas Transportation Institute (TTI) study noted that the decision to apply signal control at ramp terminals should be based on an evaluation of traffic signal warrants. Both ramp terminals should use the same traffic control regardless of how the ramps are controlled (*5*). The *Facilities Development Manual* of the Wisconsin Department of Transportation suggests that compared with signalized intersections, roundabouts are desirable when the subject interchange typically has a high proportion of left-turn flows from the off-ramps and to the on-ramps during certain peak periods, combined with limited queue storage space on bridge crossings, off-ramps, or arterial approaches (*6*). The manual also advises that in almost all cases, if the roundabout operates below capacity, the performance of the on-ramp is likely to be better than if the interchange is signalized.

The HCM uses control delay as the performance measure for signalized intersections at diamond interchanges, and control delay is specified by 14 possible movements—O-Ds—at the interchange (*3*). The HCM also provides a table that associates ranges of delay for the O-Ds with a level of service (LOS). Specifically, the LOS for each O-D movement is based on the total average control delay experienced by the traffic as it travels through the interchange. In other words, the total control delay is the sum of the average control delay at each involved signalized intersection along the path. Similar to signalized intersections, LOS assessment for roundabouts at ramp terminals is also based on control delay (*3*). The HCM also gives delay-based LOS criteria for roundabouts at ramp terminals. The delay LOS thresholds for roundabout interchanges compared with the signalized diamond interchanges are generally lower, since drivers would likely expect lower delays at roundabouts. However, the HCM does not provide a method to directly estimate control delay for roundabout interchanges. Instead, it is suggested that the procedure for analyzing an isolated roundabout can be used to estimate the capacity and delay for each roundabout at the interchange. The HCM method uses a deterministic model to estimate control delay. This deterministic delay model may not be able to well represent real-world roundabout operations, which are exactly stochastic.

In summary, although qualitative research has been conducted with regard to consideration between roundabout and signalized interchanges, there is a lack of a comprehensive operational study that quantitatively compares the double-lane roundabout and the signalized interchange. In addition, the HCM does not provide a method that directly models the control delay of the O-D movements of roundabout interchanges. Moreover, the current deterministic delay model as outlined in the HCM might not be able to accurately describe the real-world stochastic operations at roundabouts at ramp terminals. Therefore, there is an urgent need for a comprehensive and quantitative study that can address these research gaps.

SIMULATION MODELING

The objective of this research involves stochastically modeling the delay at entrances of roundabouts at ramp terminals, and, thus, the operational performance of roundabouts can be accurately evaluated. Since the deterministic methods outlined in the HCM are not sufficient to address traffic dynamics in real-world operations, a microsimulation-based stochastic method was used in this research to evaluate the operational performance of double-lane roundabouts and signalized intersections at an interchange with consideration of different traffic and geometric conditions.

Simulation Models

Vissim was used to build the simulation model for the double-lane roundabout interchange. Figure 1*a* illustrates the simulation model. Although most commercial microscopic traffic simulation software packages offer the capability of building roundabout simulation models, Vissim was chosen because it is the most widely applied microscopic simulation package for modeling roundabouts (*7–17*). Table 1 summarizes key characteristics of the double-lane roundabout interchange simulation model.

The simulation model for the double-lane signalized diamond interchange was converted from the roundabout simulation model to minimize the difference between the two models. The right-turn lane on the arterial was yield-controlled, and the right-turn lane on the off-ramps was stop-controlled. Traffic signals were installed at the entrance of both intersections. The gap acceptance behavior on all the bypass right-turn lanes was the same as that in the double-lane roundabout interchange simulation model. Key characteristics of the signalized diamond interchange simulation model were the same as those for the roundabout interchange, as summarized in Table 1. TTI phasing with two controllers was used, since it is commonly used at isolated interchanges with relatively consistent, heavy ramp volumes (*5*).

Calibration of Model for Double-Lane Roundabout Interchange

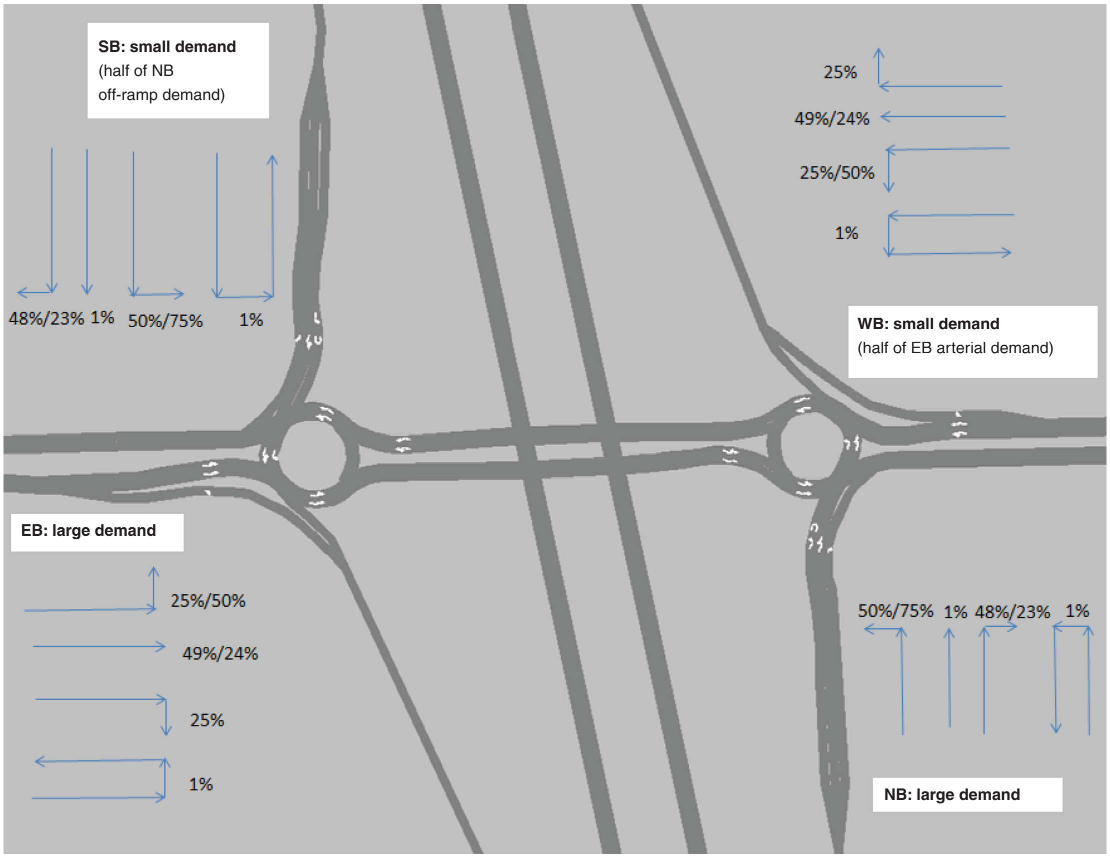
Previous research by the authors developed calibration guidelines for modeling roundabouts in Vissim (*17*). The guidelines are based on the theory that roundabout capacity is solely determined by the critical headway and follow-up headway, as represented by the following HCM equation (*3*):

$$C_{\text{pce}} = Ae^{(-Bv_c)} \tag{1}$$

$$A = \frac{3{,}600}{t_f} \qquad B = \frac{t_c - \left(\frac{t_f}{2}\right)}{3{,}600} \tag{2}$$

where

C_{pce} = lane capacity in passenger-car equivalents (pc/h),
A = coefficient A,
e = e constant,
B = coefficient B,
v_c = conflicting flow (pc/h),
t_c = critical headway (s), and
t_f = follow-up headway (s).



(a)

(b)

FIGURE 1 Double-lane interchange simulation models: (*a*) roundabout and (*b*) signalized.

TABLE 1 Characteristics of Double-Lane Roundabout Interchange Simulation Model

Characteristic	Value
Off-ramp length	2,500 ft
Arterial approach length	5,000 ft
Distance between roundabouts	700 ft/400 ft
Arterial movement distribution	
Left turn	25%/50% (heavy arterial left-turn mode)
Through	49%/24% (heavy arterial left-turn mode)
Right turn	25%
U-turn	1%
Off-ramp movement distribution	
Left turn	50%/75% (heavy off-ramp left-turn mode)
Through	1%
Right turn	48%/23% (heavy off-ramp left-turn mode)
U-turn	1%
Bypass right-turn lane	Both arterial and off-ramp entrance
Freeway 85th percentile speed	75 mph
Arterial 85th percentile speed	45 mph
Off-ramp left- and right-turn storage length	400 ft
Arterial right-turn bypass lane storage length	320 ft
Traffic volume distribution on off-ramp lanes	
Left lane	Left turn and U-turn (50% of all left turns and 100% of all U-turns)
Middle lane	Left turn and through (50% of all left turns and 100% of all through movement)
Right lane	Right turn only (100% of all right turns)
Traffic volume distribution on arterial lanes	
Left lane	Left turn, through, and U-turn (100% of all left turns, 25% of all through movement, and 100% of all U-turns)
Middle lane	Through only (75% of all through movement)
Right lane	Right turn only (100% of all right turns)

Therefore, the simulated critical headway and follow-up headway are the surrogate measures of the simulated roundabout capacity. Based on this premise, the calibration goal was matching the simulated critical headway and follow-up headway to the target critical headway and follow-up headway. The method for estimating the simulated critical headway and follow-up headway from Vissim's output data is similar to the method used in collecting field-observed gap acceptance data by measuring accepted and rejected gaps.

Calibration of the simulation model for roundabouts at ramp terminals was simply calibrating Vissim parameters to achieve the objective that the simulated t_c and t_f of each entrance lane would equal the target t_c and t_f. The critical headway and follow-up headway recommended by the Wisconsin Department of Transportation to define the roundabout capacity were 4.0 s and 2.8 s, respectively, for multilane roundabouts (*6*). These numbers became the target t_c and t_f for calibrating the simulation models for double-lane roundabouts at ramp terminals. Previous research has identified that heavy vehicles have longer critical and follow-up headways than passenger cars (*2*). To best represent the real-world conditions, the target t_c and t_f for heavy vehicles in the simulation models were set to 1 s longer than the numbers, namely, 5.0 s and 3.8 s, for multilane roundabouts. The calibration process involved adjusting Vissim parameters iteratively until the simulated t_c and t_f of each entrance lane matched the target t_c and t_f. Vissim parameters that were adjusted iteratively in the calibration process include (*a*) minimum gaps in priority rules for passenger cars and heavy vehicles, (*b*) minimum headways in priority rules for passenger cars and heavy vehicles, (*c*) speed distributions in reduced-speed areas for passenger cars and heavy vehicles, and (*d*) additive and multiplicative parts in the Wiedemann 74 car-following model (*18*), which affect the t_c and t_f for both passenger cars and heavy vehicles.

Each entrance lane of each of the two roundabouts in the simulation model was calibrated independently via dedicated calibration iterations. The iteration involved calibration of t_c and t_f for either passenger cars or heavy vehicles. In each iteration step, one or more of the aforementioned Vissim parameters were adjusted. Thirty simulation runs were conducted for each iteration step. Each simulation run lasted 4,500 simulation seconds with the first 900 simulated seconds as the warm-up period, which was excluded from the sample for estimating the simulated t_c and t_f. The simulation resolution was five simulation steps per second. After each iteration step, the mean and the standard deviation of the 30 simulated t_c and t_f were calculated. If the mean t_c and t_f were equal to the target t_c and t_f, the iteration was completed. In total, 65 iteration steps were conducted to calibrate the entire double-lane roundabout interchange simulation model. Table 2 summarizes the calibration results.

Calibration of Model for Signalized Diamond Interchange

The major difference between the roundabout and signalized intersection is gap acceptance versus signal control. Therefore, the double-lane signalized interchange simulation model was calibrated with the same gap acceptance parameters used in the double-lane roundabout simulation model when modeling yielding behaviors at the intersection entrances. In addition, the same reduced speed areas for passenger cars and heavy vehicles, as well as the same additive and multiplicative parts in the Wiedemann 74 car-following model, were also used in the signalized interchange simulation model. Using the same parameter settings was to ensure a fair comparison between roundabouts and signalized interchanges.

METHODOLOGY

Simulation Scenarios

If the sum of entering plus circulating traffic at each entry point of a roundabout is less than 1,800 vph, a two-lane roundabout may work (*1*). From this guidance, the simulation experiment design considered different combinations of entering and circulating traffic demand as long as the sum of entering plus circulating traffic at each entrance

TABLE 2 Calibration for Double-Lane Roundabout Interchange Simulation Model

Lane Calibrated	Target t_c (s)	Simulated–Calibrated t_c (s)	Target t_f (s)	Simulated–Calibrated t_f (s)
WB Arterial (East Roundabout)				
Left lane				
PC	4.0	3.97 (0.36)	2.8	2.77 (0.67)
HV	5.0	5.02 (0.63)	3.8	3.83 (0.52)
Middle lane				
PC	4.0	4.00 (0.27)	2.8	2.79 (0.66)
HV	5.0	5.04 (0.59)	3.8	3.82 (0.54)
Bypass right-turn lane				
PC	4.2	4.17 (0.33)	2.8	2.76 (0.51)
HV	5.2	5.22 (0.45)	3.8	3.79 (0.48)
EB Arterial (West Roundabout)				
Left lane				
PC	4.0	3.98 (0.45)	2.8	2.81 (0.71)
HV	5.0	4.95 (0.55)	3.8	3.84 (0.74)
Middle lane				
PC	4.0	4.04 (0.40)	2.8	2.80 (0.67)
HV	5.0	5.04 (0.63)	3.8	3.82 (0.55)
Bypass right-turn lane				
PC	4.2	4.22 (0.39)	2.8	2.78 (0.49)
HV	5.2	5.17 (0.48)	3.8	3.84 (0.58)
NB Off-Ramp (East Roundabout)				
Left lane				
PC	4.0	3.98 (0.37)	2.8	2.75 (0.61)
HV	5.0	5.00 (0.53)	3.8	3.84 (0.62)
Middle lane				
PC	4.0	4.00 (0.39)	2.8	2.78 (0.63)
HV	5.0	4.99 (0.50)	3.8	3.84 (0.69)
Bypass right-turn lane				
PC	4.2	4.17 (0.16)	2.8	2.76 (0.68)
HV	5.2	5.15 (0.50)	3.8	3.82 (1.07)
SB Off-Ramp (West Roundabout)				
Left lane				
PC	4.0	4.01 (0.34)	2.8	2.83 (0.61)
HV	5.0	4.95 (0.60)	3.8	3.83 (0.58)
Middle lane				
PC	4.0	4.04 (0.45)	2.8	2.84 (0.84)
HV	5.0	4.99 (0.46)	3.8	3.84 (0.70)
Bypass right-turn lane				
PC	4.2	4.15 (0.18)	2.8	2.78 (0.69)
HV	5.2	2.78 (0.69)	3.8	3.75 (1.20)
WB Interior (West Roundabout)				
Left lane				
PC	4.0	4.01 (0.39)	2.8	2.79 (0.64)
HV	5.0	5.04 (0.59)	3.8	3.84 (0.61)
Right lane				
PC	4.0	3.95 (0.44)	2.8	2.84 (0.59)
HV	5.0	4.98 (0.53)	3.8	3.81 (0.58)
EB Interior (East Roundabout)				
Left lane				
PC	4.0	3.99 (0.38)	2.8	2.82 (0.62)
HV	5.0	4.97 (0.57)	3.8	3.77 (0.49)
Right lane				
PC	4.0	4.00 (0.41)	2.8	2.75 (0.63)
HV	5.0	5.03 (0.61)	3.8	3.79 (0.55)

NOTE: WB = westbound. Numbers in parentheses represent standard deviation. HV = heavy vehicle; EB = eastbound; NB = northbound; SB = southbound.

point was less than 2,550 vph. Asymmetric traffic demand at the two roundabouts and intersections was assumed and modeled in the simulation experiment as illustrated in Figure 1, considering that balanced traffic demand at an interchange is not common in reality. The northbound (NB) off-ramp and the eastbound (EB) arterial had larger traffic demand, whereas the traffic demand at the southbound (SB) off-ramp and the westbound (WB) arterial was halved. This setting created critically heavy circulating and entering traffic at the NB off-ramp entrance of the east roundabout, as well as light circulating and entering traffic at the SB off-ramp entrance of the west roundabout. This traffic demand setting was applied to both roundabouts and signalized diamond interchanges.

In addition to various combinations of traffic demand, the effects of heavy-vehicle percentages of ramp traffic were considered in the experiment design. Five different heavy-vehicle percentages were examined: 5%, 10%, 15%, 20%, and 25%. Moreover, heavy arterial left-turn scenarios (50% of arterial traffic turning left to the on-ramp) versus normal left-turn scenarios (25% of arterial traffic turning left to the on-ramp) were considered in the experiment design. In addition, heavy off-ramp left-turn scenarios (75% of off-ramp traffic turning left) versus normal left-turn scenarios (50% of off-ramp traffic turning left) were modeled in the experiments.

Ramp spacing is another factor that was considered in the experiment design. Since most freeway interchanges have 300- to 700-ft ramp spacing, 400-ft and 700-ft ramp spacing were the two cases included in the experiment design. With all scenarios considered incorporated in the experiment design, 2,880 unique scenarios with combinations of different traffic demand, heavy-vehicle percentages, ramp spacing, and arterial and off-ramp left-turn percentages were created for double-lane roundabouts and signalized diamond interchanges. Each scenario was examined by a simulation experiment, and each experiment was performed with 30 simulation runs with different random seeds. Each simulation run lasted 4,500 simulation seconds with the initial 900 warm-up seconds excluded from the sample for analysis.

For each individual experiment for signalized diamond interchanges, the signal timing was optimized based on the specific combination of intersection spacing and traffic conditions using PASSER III-98. The authors initially explored methods to model the TTI phasing in Synchro. However, it turned out that Synchro only supported ring-barrier phasing and was not appropriate for modeling TTI phasing.

Performance Measure and Method of Analysis

Since the HCM uses control delay to define the LOS of interchanges, control delay and LOS were, therefore, the performance measures used in the analysis and comparison. The HCM defines LOS for each O-D movement at the interchange (both roundabout and signalized diamond interchanges). Each LOS for each O-D movement corresponds to a control delay threshold. Compared with the signalized interchanges, roundabout interchanges have generally smaller delay thresholds for LOS, since drivers would likely expect lower delay at roundabouts. Particularly, roundabout interchanges will have LOS F when the control delay is greater than 75 s, whereas signalized interchanges will not have LOS F until the control delay is greater than 120 s.

For each simulation experiment, 30 simulation runs were performed with different random seeds. Each simulation run output control delay for all traffic O-D movements involved in the interchange, as well as approach control delay by taking the weighted average of the control delay for all O-D movements of that approach. Control delays for all approaches were recorded, namely, the NB off-ramp approach, the SB off-ramp approach, the EB arterial approach, and the WB arterial approach. In the end, the average approach control delay from the 30 simulation runs for each approach was computed as the control delay performance measure for each experiment.

In the 2,880 simulation experiments conducted (i.e., 1,440 experiments for double-lane roundabout interchanges and 1,440 experiments for double-lane signalized diamond interchanges), a large number of combinations of different traffic demand from NB and SB off-ramps, as well as EB and WB arterial approaches were examined. These combinations of traffic demand prepared a solid and comprehensive data set to sufficiently include various traffic conditions that may occur during both off-peak and peak periods at off-ramp and arterial entrances of an interchange. With this comprehensive data set, a generalized method was developed in this research to simplify the analysis and comparison between roundabouts and signalized diamond interchanges. This method considered the operational performance at (*a*) the off-ramp entrance approach and (*b*) the arterial entrance approach rather than the operational performance for specific traffic movements. In other words, NB and SB off-ramps were not considered separately; rather, data from both off-ramps were integrated and both off-ramps were generalized as the "off-ramp approach." Similarly, data from EB and WB arterial approaches were also combined, and both approaches were generalized as the "arterial approach," Control delay for the off-ramp approach and for the arterial approach are the performance measures. Variables considered in the operational analysis include interchange ramp spacing, off-ramp heavy-vehicle percentage, and circulating traffic demand for roundabout interchanges or conflicting traffic demand for signalized diamond interchanges. The benefit of using this generalized analysis method was that it simplified the analysis and comparison and was more appropriate for interchange planning purposes, such as selection between roundabout and signalized diamond interchange at the planning level based on traffic demand.

FACTORS AFFECTING CONTROL DELAY

Before the control delay is analyzed, factors that significantly affect control delay were identified. Ramp spacing, sum of entering and circulating or conflicting traffic demand, and ramp heavy-vehicle percentage are potential factors that may affect the operational performance of roundabouts and signalized diamond interchanges.

Linear regression analyses were performed to identify or confirm the significant factors. In the regression analysis, a *t*-test was used to measure the significance of each potential factor involved in the regression analysis. Table 3 summarizes the test results for the effect of the potential factors on off-ramp control delay and Table 4 summarizes the test results for these factors' effect on control delay of the arterial approach.

Results from Tables 3 and 4 indicate that at double-lane roundabouts and signalized interchanges, off-ramp and arterial control delays are both sensitive to the sum of entering and circulating traffic demand. The following is a summary of the findings that shows the significant factors for both types of interchange, where E+C represents the sum of entering and circulating or conflicting traffic demand:

1. Off-ramp delay:
   – Roundabout:
     - E+C and
     - HV% and

TABLE 3 Effects of Factors on Off-Ramp and Arterial Control Delay at Double-Lane Interchanges

	Roundabout		Signal	
Variable Tested	p-Value	± Effect[a]	p-Value	± Effect
Sum of entering and circulating or conflicting traffic demands	.0001[b]	+	.0001[b]	+
Ramp spacing	.982	na	.0001[b]	+
Ramp HV percentage	.0001[b]	+	.0001[b]	+

NOTE: p-Value cutoff = .05; na = not applicable.
[a]Only applicable to statistically significant factors; positive effect indicates that increasing the value of the factor will increase the delay; vice versa for negative effect.
[b]Denotes statistically significant factors.

– Signal:
  - E+C,
  - Ramp spacing, and
  - HV%; and
2. Arterial delay:
   – Roundabout:
     - E+C,
     - Ramp spacing, and
     - HV% and
   – Signal:
     - E+C,
     - Ramp spacing, and
     - HV%.

Ramp spacing affects off-ramp control delay at double-lane signalized diamond interchanges, in which case an internal queue frequently built up when traffic volume was high. Ramp spacing also affects arterial delay at both double-lane roundabouts and signalized interchanges. The ramp heavy-vehicle percentage affects both off-ramp and arterial control delay at both types of double-lane interchanges.

ANALYSIS OF OFF-RAMP CONTROL DELAY

Double-Lane Roundabout Interchange

Figure 2*a* illustrates the relationship between off-ramp control delay and the sum of entering and circulating demand (V_c+$_e$) at the off-ramp entrance of the double-lane roundabout interchange. From the HCM, control delay greater than 75 s indicates LOS F for roundabout interchanges. Therefore, data points with a y-axis value greater than 75 s were then removed. Figure 2*b* plots all data points with control delay equal to or less than 75 s. By referring to x-axis values of appropriate data points in Figure 2*a* and *b,* the following findings were revealed:

- The off-ramp of a double-lane roundabout interchange must have LOS F when V_{c+e} is greater than 2,274 vph.
- The off-ramp of a double-lane roundabout interchange may have LOS F when V_{c+e} is between 2,125 vph and 2,274 vph.
- The off-ramp of a double-lane roundabout interchange must not have LOS F when V_{c+e} is less than 2,125 vph.

To explore the numerical relationship between off-ramp control delay and the sum of entering and circulating demand, regression analyses were performed on subsets of data points displayed in Figure 2*b* with consideration of various ramp heavy-vehicle percentages. Figure 2, *c* through *g,* illustrates the regression analysis results.

Based on these results, off-ramp control delay for double-lane roundabout interchanges was quantitatively modeled by the following equations:

For ramp HV% = 5%:

$$\begin{aligned} d_{\text{off-ramp}} &= 2.72745 \cdot 10^{-17} v_{c+e}^6 - 1.87093 \cdot 10^{-13} v_{c+e}^5 \\ &\quad + 5.0688 \cdot 10^{-10} v_{c+e}^4 - 6.83446 \cdot 10^{-7} v_{c+e}^3 \\ &\quad + 4.75911 \cdot 10^{-4} v_{c+e}^2 - 1.51289 \cdot 10^{-1} v_{c+e} + 17.6963 \\ & 400 \le v_{c+e} \le 2{,}274 \\ & R^2 = .85 \end{aligned} \tag{3}$$

TABLE 4 Effects of Factors on Arterial Control Delay at Double-Lane Interchanges

	Roundabout		Signal	
Variable Tested	p-Value	± Effect[a]	p-Value	± Effect
Sum of entering and circulating or conflicting traffic demands	.0001[b]	+	.0001[b]	+
Ramp spacing	.0001[b]	+	.0001[b]	+
Ramp HV percentage	.0001[b]	+	.001[b]	+

NOTE: p-Value cutoff = .05.
[a]Only applicable to statistically significant factors; positive effect indicates that increasing the value of the factor will increase the delay; vice versa for negative effect.
[b]Denotes statistically significant factors.

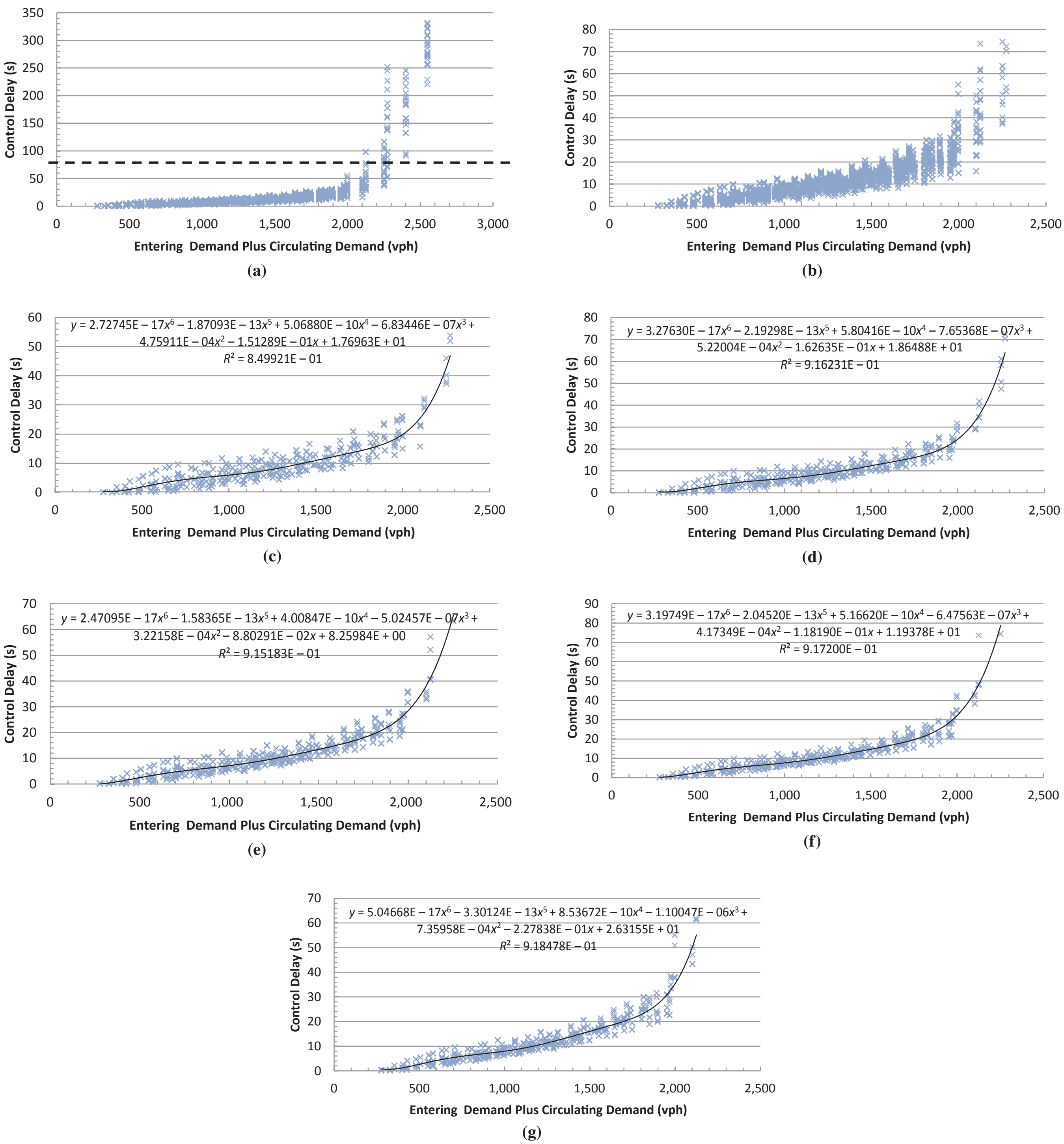


FIGURE 2 Off-ramp control delay versus traffic demand for double-lane roundabout interchanges: (*a*) all samples, (*b*) samples of control delay ≤ 75 s, (*c*) ramp heavy-vehicle percentage (HV%) = 5%, (*d*) ramp HV% = 10%, (*e*) ramp HV% = 15%, (*f*) ramp HV% = 20%, and (*g*) ramp HV% = 25% (dashed line signifies cutoff control delay that specifies LOS F for roundabouts; above dashed line, control delays indicate LOS F).

For ramp HV% = 10%:

$$d_{\text{off-ramp}} = 3.2763 \cdot 10^{-17} v_{c+e}^6 - 2.19298 \cdot 10^{-13} v_{c+e}^5 + 5.80416 \cdot 10^{-10} v_{c+e}^4 - 7.65368 \cdot 10^{-7} v_{c+e}^3 + 5.22004 \cdot 10^{-4} v_{c+e}^2 - 1.62635 \cdot 10^{-1} v_{c+e} + 18.6488$$

$$400 \leq v_{c+e} \leq 2,274$$

$$R^2 = .92 \quad (4)$$

For ramp HV% = 15%:

$$d_{\text{off-ramp}} = 2.47095 \cdot 10^{-17} v_{c+e}^6 - 1.58365 \cdot 10^{-13} v_{c+e}^5 + 4.00847 \cdot 10^{-10} v_{c+e}^4 - 5.02457 \cdot 10^{-7} v_{c+e}^3 + 3.22158 \cdot 10^{-4} v_{c+e}^2 - 8.80291 \cdot 10^{-2} v_{c+e} + 8.25984$$

$$400 \leq v_{c+e} \leq 2,274$$

$$R^2 = .92 \quad (5)$$

For ramp HV% = 20%:

$$d_{\text{off-ramp}} = 3.19749 \cdot 10^{-17} v_{c+e}^6 - 2.0452 \cdot 10^{-13} v_{c+e}^5 + 5.1662 \cdot 10^{-10} v_{c+e}^4 - 6.47563 \cdot 10^{-7} v_{c+e}^3 + 4.17349 \cdot 10^{-4} v_{c+e}^2 - 1.1819 \cdot 10^{-1} v_{c+e} + 11.9378$$

$$400 \leq v_{c+e} \leq 2,274$$

$$R^2 = .92 \quad (6)$$

For ramp HV% = 25%:

$$d_{\text{off-ramp}} = 5.04668 \cdot 10^{-17} v_{c+e}^6 - 3.30124 \cdot 10^{-13} v_{c+e}^5 + 8.53672 \cdot 10^{-10} v_{c+e}^4 - 1.10047 \cdot 10^{-6} v_{c+e}^3 + 7.35958 \cdot 10^{-4} v_{c+e}^2 - 2.27838 \cdot 10^{-1} v_{c+e} + 26.3155$$

$$400 \leq v_{c+e} \leq 2,274$$

$$R^2 = .92 \quad (7)$$

where $d_{\text{off-ramp}}$ is the off-ramp control delay in seconds and v_{c+e} is the sum of entering and circulating demand in vehicles per hour.

Double-Lane Signalized Interchange

Since ramp spacing is a significant factor that affects off-ramp control delay for two-lane (one being the arterial) signalized diamond interchanges, the data set of arterial control delay was split into two subsets: 400 ft and 700 ft. Similar methods were used to analyze and model the off-ramp control delay for double-lane signalized diamond interchanges under the 400-ft and 700-ft ramp spacing conditions. The analysis resulted in the following findings:

- Off-ramps of double-lane signalized diamond interchanges with 400-ft ramp spacing may have LOS F when V_{c+e} is equal to or greater than 1,968 vph.
- Off-ramps of double-lane signalized diamond interchanges with 400-ft ramp spacing must not have LOS F when V_{c+e} is less than 1,968 vph.
- Off-ramps of double-lane signalized diamond interchanges with 700-ft ramp spacing may have LOS F when V_{c+e} is equal to or greater than 1,388 vph.
- Off-ramps of double-lane signalized diamond interchanges with 700-ft ramp spacing must not have LOS F when V_{c+e} is less than 1,388 vph.

Figure 3, *a* through *f,* illustrates the regression analysis procedure and results for the 400-ft and 700-ft ramp spacing conditions.

Since the off-ramp control delay for double-lane signalized diamond interchanges is sensitive to the sum of entering demand and conflicting demand and the heavy-vehicle percentage under each ramp spacing category, 10 regression analyses were performed. Based on these regression analysis results, the off-ramp control delay for double-lane signalized interchanges was quantitatively modeled by the following equations:

Ramp spacing = 400 ft; heavy demand off-ramp; HV% = 5%:

$$d_{\text{off-ramp}} = 9.56081 e^{0.00048 v_{c+e}}$$

$$400 \leq v_{c+e} \leq 2,550$$

$$R^2 = .59 \quad (8)$$

Ramp spacing = 400 ft; heavy demand off-ramp; HV% = 10%:

$$d_{\text{off-ramp}} = 9.32552 e^{0.00054 v_{c+e}}$$

$$400 \leq v_{c+e} \leq 2,550$$

$$R^2 = .70 \quad (9)$$

Ramp spacing = 400 ft; heavy demand off-ramp; HV% = 15%:

$$d_{\text{off-ramp}} = 9.24043 e^{0.00057 v_{c+e}}$$

$$400 \leq v_{c+e} \leq 2,550$$

$$R^2 = .78 \quad (10)$$

Ramp spacing = 400 ft; heavy demand off-ramp; HV% = 20%:

$$d_{\text{off-ramp}} = 9.21713 e^{0.00060 v_{c+e}}$$

$$400 \leq v_{c+e} \leq 2,550$$

$$R^2 = .82 \quad (11)$$

Ramp spacing = 400 ft; heavy demand off-ramp; HV% = 25%:

$$d_{\text{off-ramp}} = 8.832841 e^{0.00064 v_{c+e}}$$

$$400 \leq v_{c+e} \leq 2,550$$

$$R^2 = .88 \quad (12)$$

Ramp spacing = 700 ft; heavy demand off-ramp; HV% = 5%:

$$d_{\text{off-ramp}} = 10.19273 e^{0.00047 v_{c+e}}$$

$$400 \leq v_{c+e} \leq 2,550$$

$$R^2 = .69 \quad (13)$$

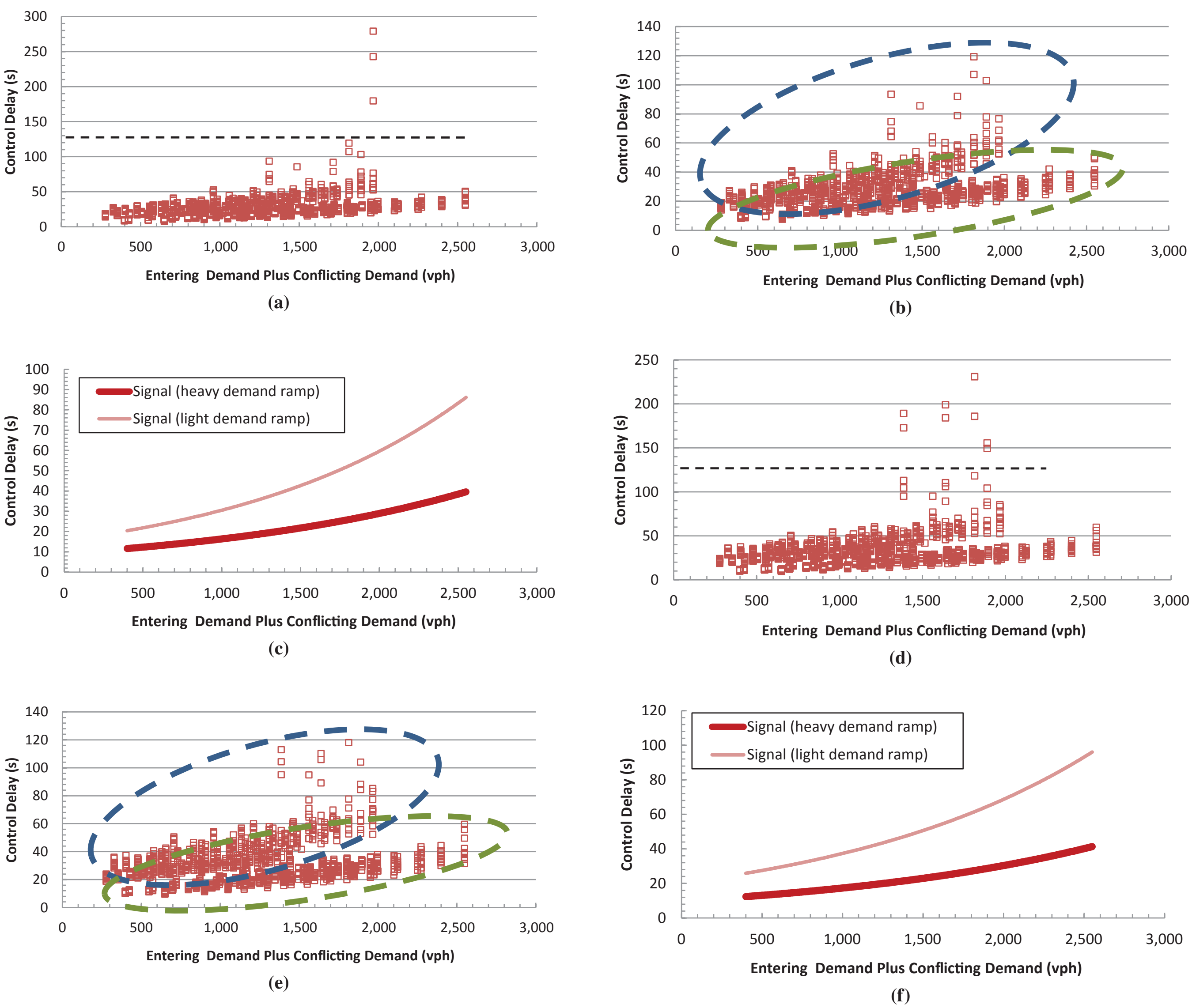


FIGURE 3 Regression analysis procedure for off-ramp control delay at double-lane signalized diamond interchanges: (*a*, *b*, *c*) 400-ft ramp spacing and (*d*, *e*, *f*) 700-ft ramp spacing (dashed line signifies cutoff control delay that specifies LOS F for signalized intersection; above dashed line, control delays indicate LOS F).

Ramp spacing = 700 ft; heavy demand off-ramp; HV% = 10%:

$$d_{\text{off-ramp}} = 9.9179e^{0.00054 v_{c+e}}$$
$$400 \le v_{c+e} \le 2{,}550$$
$$R^2 = .79 \tag{14}$$

Ramp spacing = 700 ft; heavy demand off-ramp; HV% = 15%:

$$d_{\text{off-ramp}} = 9.85112e^{0.00058 v_{c+e}}$$
$$400 \le v_{c+e} \le 2{,}550$$
$$R^2 = .84 \tag{15}$$

Ramp spacing = 700 ft; heavy demand off-ramp; HV% = 20%:

$$d_{\text{off-ramp}} = 9.8135e^{0.00060 v_{c+e}}$$
$$400 \le v_{c+e} \le 2{,}550$$
$$R^2 = .86 \tag{16}$$

Ramp spacing = 700 ft; heavy demand off-ramp; HV% = 25%:

$$d_{\text{off-ramp}} = 9.70303e^{0.00061 v_{c+e}}$$
$$400 \le v_{c+e} \le 2{,}550$$
$$R^2 = .88 \tag{17}$$

where $d_{\text{off-ramp}}$ is the off-ramp control delay in seconds, and v_{c+e} is the sum of entering and conflicting demands in vehicles per hour.

Comparison of Off-Ramp Operational Performance

Comparison of off-ramp control delay was conducted for 400-ft and 700-ft ramp spacing cases. One key finding from the comparison is that regardless of ramp spacing, when V_{c+e} is greater than 2,274 vph, the off-ramp of a double-lane signalized diamond interchange may work, whereas the off-ramp of a double-lane roundabout interchange has LOS F.

Comparison Under $V_{c+e} \le 2{,}274$ vph

Figure 4, *a* through *t*, illustrates the comparison of off-ramp control delay and off-ramp LOS under different scenarios of ramp heavy-vehicle percentages. The control delays were computed based on the regression analysis results. According to Figure 4, off-ramp control delay for double-lane roundabout interchanges is less than that for double-lane signalized diamond interchanges when the traffic demand is not very high under any ramp heavy-vehicle percentage condition. The difference in off-ramp control delay decreases as the sum of entering and circulating demand increases. Conclusions from the comparison are as follows:

- For 400-ft ramp spacing: under 5%, 10%, 15%, 20%, and 25% ramp traffic conditions, the off-ramp of double-lane signalized diamond interchanges starts to have better LOS when V_{c+e} reaches 2,095 vph, 2,010 vph, 1,950 vph, 1,900 vph, and 1,860 vph, respectively.
- For 700-ft ramp spacing: under 5%, 10%, 15%, 20%, and 25% ramp traffic conditions, the off-ramp of double-lane signalized diamond interchanges starts to have better LOS when V_{c+e} reaches 2,095 vph, 2,010 vph, 2,075 vph, 2,030 vph, and 2,000 vph, respectively.

ANALYSIS OF CONTROL DELAY OF ARTERIAL APPROACH

Double-Lane Roundabout Interchange

Since ramp spacing is a significant factor that affects arterial control delay for double-lane roundabout diamond interchanges, the data set of arterial control delay was split into two subsets: 400 ft and 700 ft. Similar methods were used to analyze and model the arterial control delay for double-lane roundabout diamond interchanges under the 400-ft and 700-ft ramp spacing conditions. The analysis resulted in the following findings:

- Regardless of ramp spacing, the arterial approach of double-lane roundabout interchanges with 400-ft ramp spacing may have LOS F when V_{c+e} is equal to or greater than 1,974 vph.
- Regardless of ramp spacing, the arterial approach of double-lane roundabout interchanges with 400-ft ramp spacing must not have LOS F when V_{c+e} is less than 1,974 vph.

Since arterial control delay for double-lane roundabout diamond interchanges is sensitive to the sum of entering demand and conflicting demand and heavy-vehicle percentages under each ramp spacing category, 10 regression analyses were performed, and regression equations were recorded.

Double-Lane Signalized Interchange

Similar methods were used to analyze and model the arterial control delay for double-lane signalized diamond interchanges under the 400-ft and 700-ft ramp spacing conditions. Since ramp spacing is a significant factor affecting arterial control delay, the data set of arterial control delay was split into two subsets: 400 ft and 700 ft. The analysis resulted in the following findings:

- The arterial approach of double-lane signalized diamond interchanges with 400-ft ramp spacing may have LOS F when V_{c+e} is equal to or greater than 1,742 vph.
- The arterial approach of double-lane signalized diamond interchanges with 400-ft ramp spacing must not have LOS F when V_{c+e} is less than 1,742 vph.
- The arterial approach of double-lane signalized diamond interchanges with 700-ft ramp spacing may have LOS F when V_{c+e} is equal to or greater than 1,566 vph.
- The arterial approach of double-lane signalized diamond interchanges with 700-ft ramp spacing must not have LOS F when V_{c+e} is less than 1,566 vph.

Since arterial control delay for double-lane signalized interchanges is sensitive to the sum of entering and conflicting demand and heavy-vehicle percentages under each ramp spacing category, 10 regression analyses were performed, and regression equations were recorded.

Comparison of Arterial Operational Performance

Comparison of arterial control delay was conducted for 400-ft and 700-ft ramp spacing. The corresponding arterial LOS was also computed based on the arterial control delay. The full comparison results are summarized in Figure 5, *a* through *t*. The conclusion of the comparison is that regardless of ramp spacing, the arterial of

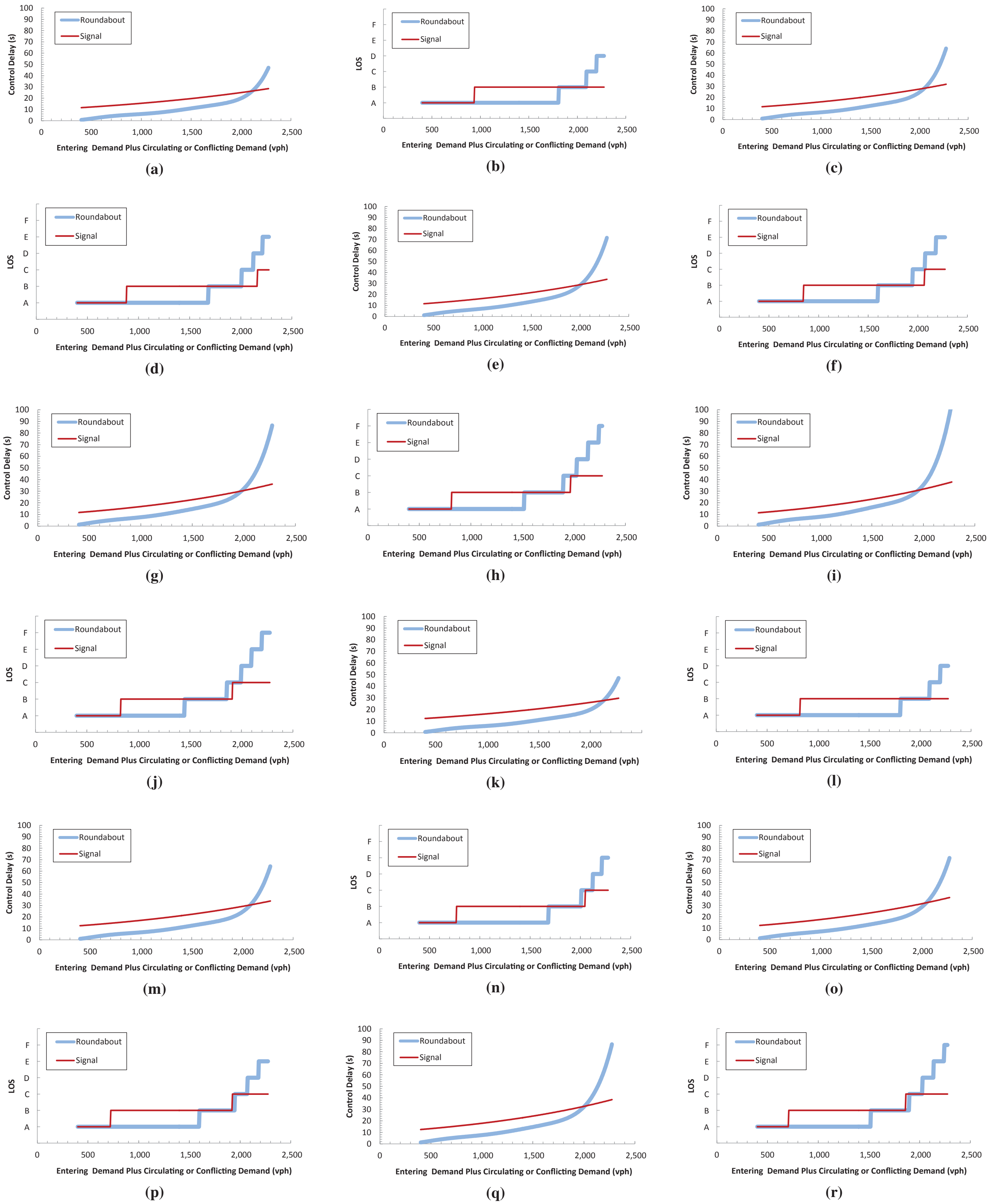


FIGURE 4 Comparison of off-ramp control delay and LOS between double-lane roundabout and signalized diamond interchange: (*a*, *c*, *e*, *g*, *i*) control delay for HV% = 5%, 10%, 15%, 20%, 25%, respectively; ramp spacing = 400 ft; (*b*, *d*, *f*, *h*, *j*) LOS for HV% = 5%, 10%, 15%, 20%, 25%, respectively; ramp spacing = 400 ft; (*k*, *m*, *o*, *q*) control delay for HV% = 5%, 10%, 20%, respectively; ramp spacing = 700 ft; and (*l*, *n*, *p*, *r*) LOS for HV% = 5%, 10%, 15%, 20%, respectively; ramp spacing = 700 ft.

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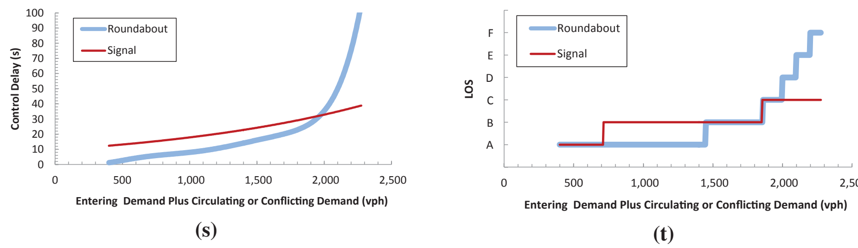

FIGURE 4 *(continued)* Comparison of off-ramp control delay and LOS between double-lane roundabout and signalized diamond interchange: (*s*) control delay for HV% = 25%, ramp spacing = 700 ft; and (*t*) LOS for HV% = 25%, ramp spacing = 700 ft.

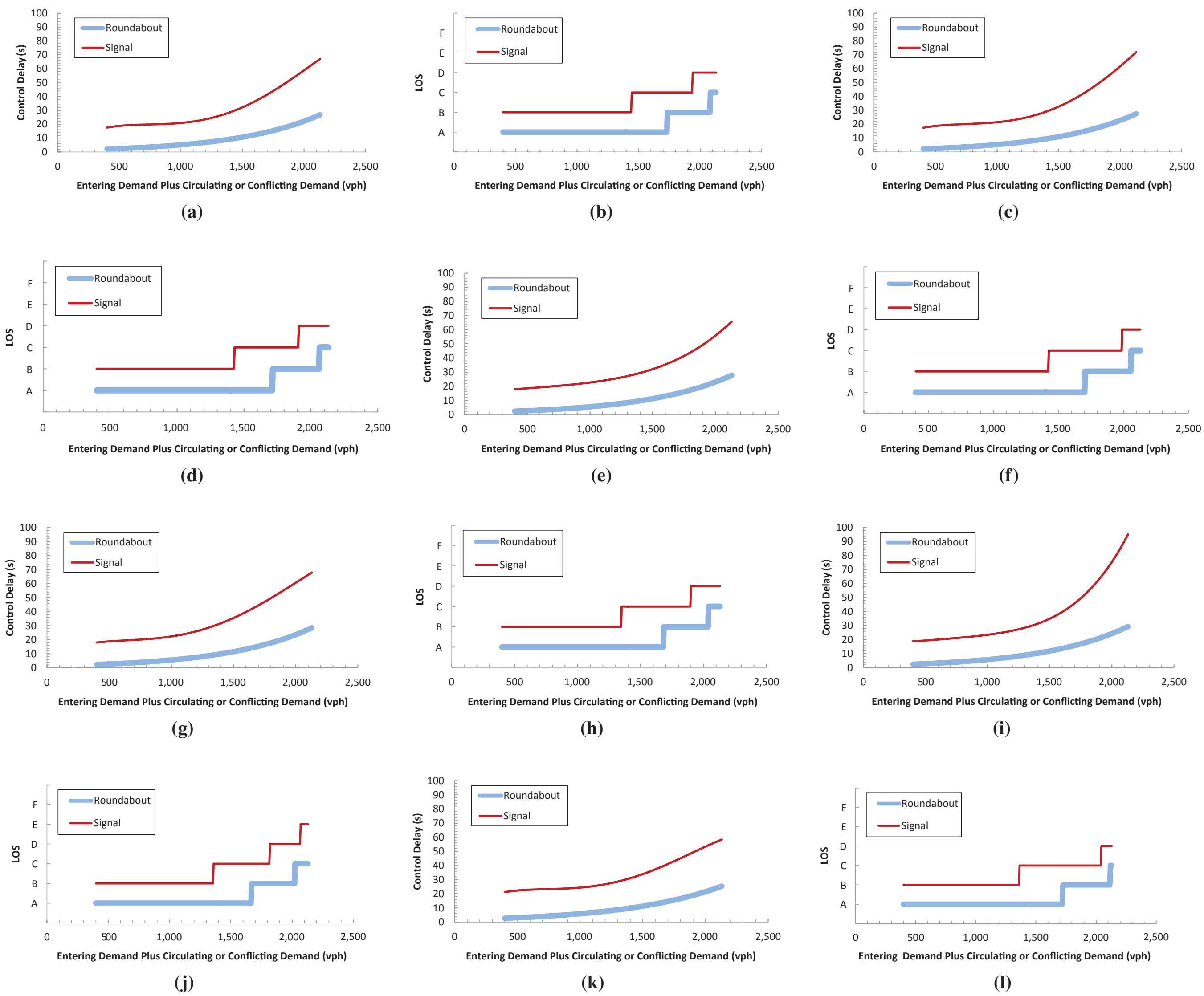

FIGURE 5 Comparison of arterial control delay and LOS between double-lane roundabout and signalized diamond interchange: (*a, c, e, g, i*) control delay for HV% = 5%, 10%, 15%, 20%, 25%, respectively; ramp spacing = 400 ft; (*b, d, f, h, j*) LOS for HV% = 5%, 10%, 15%, 20%, 25%, respectively; ramp spacing = 400 ft; (*k*) control delay for HV% = 5%; ramp spacing = 700 ft; and (*l*) LOS for HV% = 5%; ramp spacing = 700 ft (400 vph are less than or equal to entering demand plus circulating or conflicting demand less than or equal to 2,130 vph).

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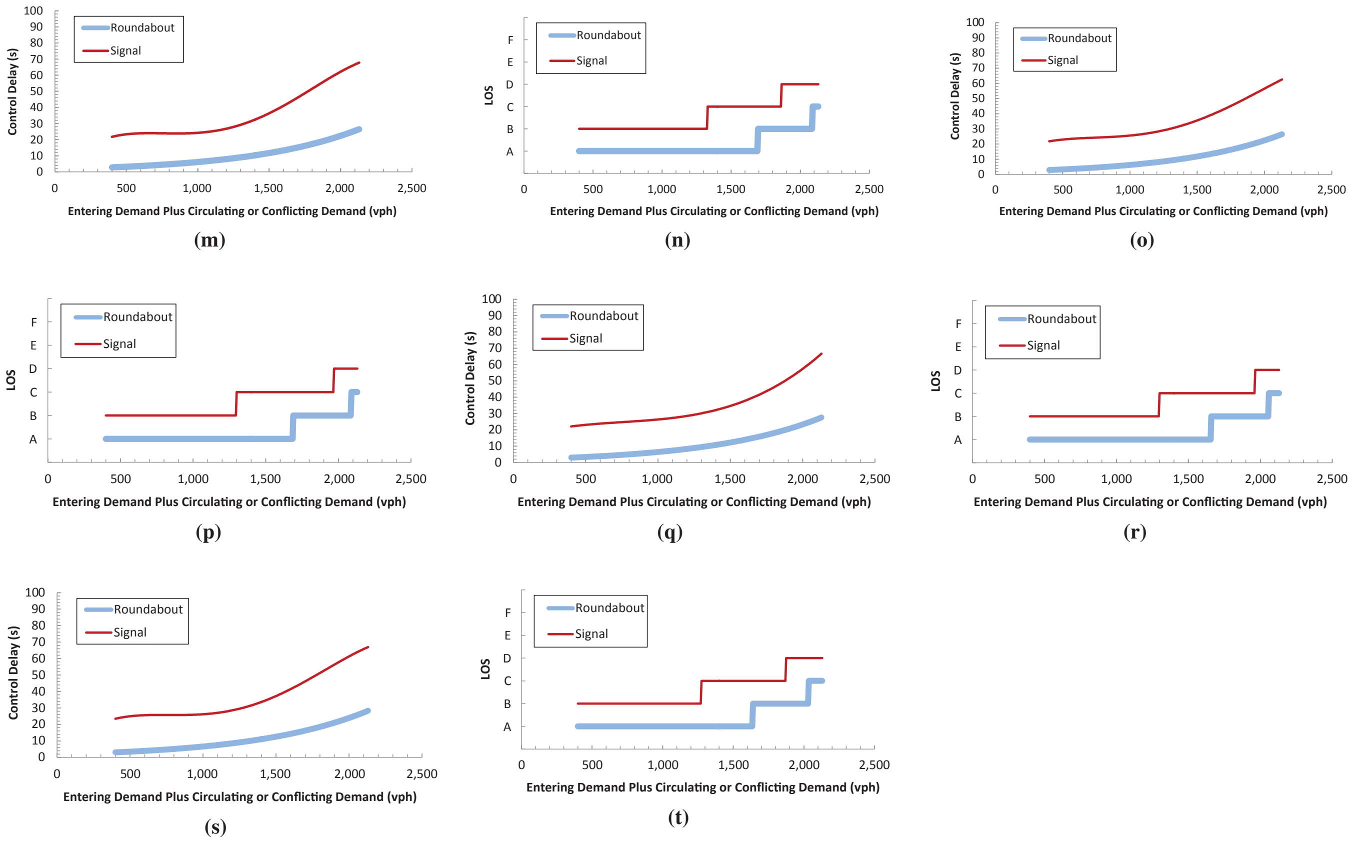

FIGURE 5 *(continued)* **Comparison of arterial control delay and LOS between double-lane roundabout and signalized diamond interchange: (*m*, *o*, *q*, *s*) control delay for HV% = 10%, 15%, 20%, 25%, respectively; ramp spacing = 700 ft; and (*n*, *p*, *r*, *t*) LOS for HV% = 10%, 15%, 20%, 25%, respectively; ramp spacing = 700 ft (400 vph are less than or equal to entering demand plus circulating or conflicting demand less than or equal to 2,130 vph).**

double-lane roundabout interchanges has a better LOS than that of a double-lane signalized diamond interchange at any V_{c+e} conditions and under all ramp heavy-vehicle percentages.

GUIDELINES FOR SELECTION BETWEEN DOUBLE-LANE ROUNDABOUT AND SIGNALIZED INTERCHANGE

The guidelines were developed on the basis of the comparison results of the operational performance of roundabouts and signalized diamond interchanges. In particular, the LOS was used as the sole criterion of operational performance when judging between roundabouts and signalized diamond interchanges. In case the roundabout interchange and the signalized interchange have the same LOS, the roundabout interchange will be recommended since road users experience less delay at roundabouts when the LOSs are the same. The guidelines do consider factors including ramp spacing, off-ramp heavy-vehicle percentage, and difference between entering and circulating demand when applicable. The guidelines are provided in the form of a lookup table based on the sum of entering and circulating demand. Conditions when a signalized or roundabout interchange is appropriate are summarized in Table 5. In general, the roundabout interchange performs better than the signalized interchange if the sum of entering and conflicting demand is under a certain threshold.

TABLE 5 Lookup Table for Selection Between Double-Lane Interchanges

	V_{c+e} (vph)	
Condition	Select Signal	Select Roundabout
Ramp Spacing = 400 ft		
Off ramp approach		
HV% = 5%	≥2,095	<2,095
HV% = 10%	≥2,010	<2,010
HV% = 15%	≥1,950	<1,950
HV% = 20%	≥1,900	<1,900
HV% = 25%	≥1,860	<1,860
Arterial approach		
All HV%	None	≤2,130
Ramp Spacing = 700 ft		
Off ramp approach		
HV% = 5%	≥2,095	<2,095
HV% = 10%	≥2,010	<2,010
HV% = 15%	≥2,075	<1,145
HV% = 20%	≥2,030	<1,135
HV% = 25%	≥2,000	<1,100
Arterial approach		
All HV%	None	≤2,130

CONCLUSIONS

Based on the results of the comparison between double-lane signalized diamond interchanges and roundabout interchanges, guidelines for selection between roundabout and signalized interchange were developed and presented in the form of a lookup table summarized in Table 5. In general, the selection guidelines are simply summarized as follows:

- Off-ramp approach:
  – Ramp spacing = 400 ft. Roundabout interchange is recommended when V_{c+e} is below a certain threshold ranging between 2,095 vph and 1,860 vph, depending on the off-ramp heavy-vehicle percentage.
  – Ramp spacing = 700 ft. Roundabout interchange is recommended when V_{c+e} is below a certain threshold ranging between 2,095 vph and 2,000 vph, depending on the off-ramp heavy-vehicle percentage.
- Arterial approach. Roundabout interchange consistently has better LOS under any conditions.

In conclusion, the information presented here, particularly the selection guidelines, can assist transportation professionals in determining the appropriate interchange type when future interchange construction is planned. Future research will investigate the comparison between roundabout interchanges and other signalized interchange types with different phasing scenarios.

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