**Publish Information**: Xu, H.\*, H. Liu, and Z. Tian (2011). "Control Delay Calculation at Diverging Diamond Interchanges." Transportation Research Record, No.2257, 121-130.

# **Control Delay Calculation at Diverging Diamond Interchanges**

Hao Xu (Corresponding Author) Department of Civil & Environmental Engineering Texas Tech University Lubbock, TX 79409-1023 Phone: (806) 786-0934 E-mail: hao.xu@ttu.edu

Hongchao Liu Department of Civil & Environmental Engineering Texas Tech University Lubbock, TX 79409-1023 Phone: (806) 742-3523 Ext. 229 E-mail: Hongchao.Liu@ttu.edu

Zong Tian Department of Civil & Environmental Engineering University of Nevada Reno Reno, NV 89557 Phone: (775) 784-1232 E-mail: zongt@unr.edu

Total Words: 4447 Total Figures: 9 Total Tables: 2 Total Combined: 7197

Submitted for presentation and publication at the 90<sup>th</sup> Annual Meeting of the Transportation Research Board

August 1, 2010

#### ABSTRACT

3 Diverging Diamond Interchange is a form of diamond interchange with growing interest from 4 traffic engineers and researchers. Conventional control delay calculation models are not effective 5 when applied to diverging diamond interchanges, because of the possible internal queue 6 spillback. This technical document describes a method to calculate control delay at diverging 7 diamond interchanges using one newly developed analytical model. The model was first developed for control delay calculations of external movements at conventional diamond 8 9 interchanges. By adding a function to calculate delay of internal movements, the new model was successfully used at diverging diamond interchanges to calculate control delay of both internal 10 movements and external movements. Simulation studies are also conducted to validate the new 11 model. This study can be used either as a stand-alone delay calculation model or as a supplement 12 13 to the existing simulation methods. The model also shows promise for use in other signalized 14 interchange configurations with two or more adjacent intersections.

15

1

2

16 Keywords: diverging diamond interchange, control delay, internal queue, spillback, traffic

- 17 signal capacity
- 18

#### 19 1. INTRODUCTION AND LITERATURE REVIEW

Interchanges, where freeways cross arterial streets, are key points in the road network, since they play a role in connecting the highway system and the local street system. Diamond interchanges are arguably the most commonly used interchange pattern at these locations in North America (1).

As today's travel demands increase, capacity and safety problems at diamond interchanges challenge traffic researchers and engineers. To decrease delay and improve capacity and safety at diamond interchanges, researchers have developed several innovative intersection designs. Tight Urban Diamond Interchange, Double Crossover Diamond Interchange, Displaced Left-Turn Interchange, Single Point Urban Interchange, Roundabout Interchange, MUT Interchange, Center Turn Overpass Interchange, Echelon Interchange and Diverging Diamond Interchange (2) are typical diamond designs with benefits for different types of traffic demands.

The diverging diamond interchange (DDI) as shown in Figure 1 can better accommodate left-turn movements onto or off the ramps. The design was suggested by Chlewicki (*3*) and developed from the concept of the synchronized split-phasing design. The diverging diamond interchange is a French import, first used in the city of Versailles, just outside Paris, in the 1970s. In America, it was first proposed at

I-75 @ US 224 in 2004. The first DDI in the United States made its debut in 2007 at the intersection of
 I-435 and Front Street in Kansas City, Missouri.

36



37 38

30 39 Figure 1 Diverging diamond interchange

The DDI design uses crossover movements to better accommodate left-turn movements and hence eliminate a phase in the signal cycle at the diamond interchange. Figure 2 shows the layout of the Diverging Diamond Interchange design. The freeway portion does not change but the movements off the ramps change for left-turns. At a diverging diamond interchange, through and left-turn traffic on the crossroads maneuvers differently from a conventional diamond interchange as the traffic crosses to the opposite side in the ramp terminals (4).

46



48 49	FIGURE 2 Typical layout of a diverging diamond interchange
50	
51	Compared with the conventional diamond interchange (tight urban diamond interchange),
52	the benefits of DDI could be summarized as the following:
53	• The DDI combines phases.
54	• The DDI has less conflict points.
55	• The DDI combines lane assignments (i.e. a lane assignment that allows left and
56	through movements).
57	• The DDI performs very efficiently when the heaviest movements are left or right
58	turning movements onto or off the ramps.
59	• The DDI increases safety.
60	• The DDI reduces the number of places where traffic must stop.
61	• The DDI greatly reduces traffic queues.
62	• The DDI increases capacity at an intersection, because the left turn signal phase is
63	eliminated.
64	• A DDI is typically less expensive to construct than a conventional diamond
65	interchange because it requires fewer lanes to provide the same capacity and
66	eliminates the need to widen bridge for turn lanes.
67	And the drawbacks of DDI as the following:
68	• DDI design may not be able to coordinate all movements effectively if they are all
69	equally as heavy.
70	• DDI design does not allow through movements from off-ramps to on-ramps.
71	• High speed crossroads have unacceptable intersection crossing angles. DDI must
72	be used on 35mph or lower speed facilities.
73	• DDI design cannot be placed where signals/driveways are too closely spaced to
74	the interchange. The queues from the nearby intersection might back up into the
75	interchange causing it to fail.
76	• There is concern with access to driveways for businesses and residents next to the
77	interchange.
/8	

79 If the DDI design has some drawbacks, its advantages are still prominent for suburban 80 diamond interchanges. Hence the DDI design attracts growing interest from traffic researchers 81 and engineers. Simulation methods are normally used to analyze DDI designs, especially to 82 obtain control delay which is the primary measure for determination of the level of service of 83 signalized intersections. Simulation methods are advantageous in conducting "what if" studies 84 and testing the scenarios and phenomenon that may not occur or are hard to capture in the field. 85 Nonetheless, simulation approaches are usually less effective in providing generalized results. 86 For this reason, a combined analytical and simulation approach would be ideal for control delay 87 analysis.

88 In the past several decades, mathematical models for calculating control delay have been 89 studied extensively by numerous researchers. Notable works include, but are not limited to Beckmann et al. (5) and Webster (6), who developed and tested their fundamental delay models 90 91 through simulation, and van Zuylen and Viti (7), who provided comprehensive summaries of 92 analytical delay models and improved some of them. Currently, the commonly used method is 93 described in Chapter 16 of the Highway Capacity Manual (HCM), 2000 edition (8), which came 94 from the model developed by Fambro and Rouphail (9). In review of these models, one can find 95 that most of them were developed on the basis of the assumption that the subject intersection 96 should not be blocked by queues spilled over from the downstream intersection, which is not 97 realistic in the real world. Therefore, those models work reasonably well for isolated 98 intersections, but are not as effective when applied to diamond interchanges, because of possible 99 internal queue spillback. Several researchers improved delay calculation models by taking into 100 account signal coordination in their models, such as Fambro (10) and van Zuylen (7), however, 101 with the improved models, the control delay of two major external approaches (i.e., the through 102 movements of the arterial street and the left-turn movements of the frontage roads) still cannot be 103 satisfactorily formulated to reflect the real situation.

104 The delay model in Chapter 16 of HCM 2000 is used to estimate control delays at 105 diamond interchanges by many traffic analysis tools, such as Synchro 5 and PASSER III. The 106 results, however, do not realistically reflect the actual situation when spillback of internal queue 107 occurs. To address this problem, several methods were developed and employed in traffic 108 analysis tools. Elefteriadou et al. (11) introduced a method, dubbed the Elefteriadou model in 109 this paper, to address this issue. However, the study by Hao et al. (12) found that the Elefteriadou 110 model tends to overestimate delay at diamond intersections with low overlap time (the overlap time is the difference between upstream and downstream start of the green signal.). Synchro 7 111 112 also introduced a new series of traffic analysis tools (called Queue Interactions), which look at 113 how queues may reduce capacity through spillback, starvation, and storage blocking between lane groups. A new queue delay factor was introduced to measure the additional delay incurred 114 115 by the capacity reduction due to queues on short links. The new models are used for delay 116 calculation of diamond interchanges by Synchro 7, but the specifics of this model were not published. It was also found that Synchro significantly overestimates delay at diamond 117 118 interchanges with high overlap time (12).

One analytical model for control delay of external movements at tight urban diamond interchanges was developed by Xu et al (12). The new method took into account the effects of spillback and applies an analytical approach to predict control delay. In this paper, the model was applied to calculate control delay at diverging diamond interchange with a newly developed approach for control delay calculation of internal movements. Owing to the difficulty of reproducing the studied cases in the field, we used SimTraffic 7 simulation to develop the scenarios and verify the performance of the new method.

126

# 127 2. DELAY CALCULATION AT DIVERGING DIAMOND INTERCHANGES

The diverging diamond interchange switches traffic over to the opposite side of the roadway within the interchange. This promotes left-turn movements and eliminates the left turn signal phase improving the interchange's efficiency. This simple switch improves capacity and minimizes the length of the queues which can normally cause failure within a conventional diamond interchange.

133 Two traffic signals are needed for diverging diamond interchange operation, one at each 134 crossover. Two typical signal phasing designs at diverging diamond interchanges are demonstrated in Figure 3. If the base DDI signal phasing is used, the arterial road through traffic 135 136 is controlled by signals and the off-ramp traffic is controlled by stop or yield signs. If the 137 advanced signal phasing is used, the off-ramp traffic is also controlled by signals. The 138 movements marked with green arrows and phase numbers in Figure 3 are movements controlled by traffic signals. In this paper, the developed method is appropriate only for the advanced DDI 139 140 signal phasing rather than the base DDI signal phasing, because of the particularity of delay 141 calculation for stop and yield control.



142 143

### Figure 3 Signal phasing designs at diverging diamond interchanges#

144 The internal queue may overflow, because of the limited interior spacing. In that case, 145 spillback occurs and blocks the external movements, which could cause problems on calculating 146 control delay.

147

# 148 2.1 Traffic Movement Analysis and Calculation of Lost Green Time for External 149 Movements

150 In this paper external movements were defined as the through traffic on arterial streets and leftturn traffic onto or off ramps. In order to calculate lost green time caused by internal queue, the 151 152 external traffic movements were classified into two modes. Traffic movement mode 1 is that the volume of the traffic moving through the upstream intersection in the interval of overlap time is 153 154 less than the traffic volume that the internal space can contain, as shown in FIGURE 4. It means 155 the internal queue spillback happens after the overlap time. Traffic movement mode 2 is that the 156 volume of traffic moving through the upstream intersection in the interval of overlap time is 157 more than the traffic volume that the internal space can contain, as shown in FIGURE 5. It 158 means the internal queue spillback happens during the overlap time. Both the two situations could happen with oversaturated traffic or undersaturated traffic. When the upstream start of 159 green signal is earlier than the downstream start of green signal in one cycle, the overlap value is 160 a positive number. When the downstream start of green signal is earlier than the upstream start of 161 green signal in one cycle, the overlap value is zero. Thus the overlap time value will not be 162 negative with the definition above. Since impact of the internal queue on the arterial through 163 movements and impact on the ramp left-turn movements are similar, the analysis was 164 165 emphasized on the arterial through movements. The calculation of lost green time of the two traffic movement modes are introduced in the following. 166





173 Traffic volume per lane moving through the upstream intersection during overlap time is calculated by the 174 following formula.  $V_{o-E} = \min((\frac{(o+r) \cdot q}{3600 \cdot n}), (\frac{o \cdot s}{3600 \cdot n}))$ (1)175  $V_{O-E}$  = traffic volume of each lane moving through the upstream intersection 176 during overlap time; 177 o = overlap time of the external arterial movement; 178 179 r = red time of the external arterial through movement in one cycle; 180 q = the arrival traffic flow rate of the external arterial through movement; n = the number of lanes in the lane group of the external arterial through 181 182 movement; 183 s = the saturated traffic flow rate of the external arterial through movement. 184 Thus the traffic movement mode 1 occurs when the following inequality is met: 185  $V_{O-F} \cdot L \leq I'$ (2)L = the average length of space occupied by one vehicle in the queue; 186 I' = the distance between the upstream intersection and the end of the internal 187 188 queue;  $I' = I - Q_{II}$ 189 (3)190 I = internal space length of the diamond interchange;  $Q_{II}$  = length of the queue left in the internal space at the end of the last phase. 191 The external arterial through movement with its green light indication will not be blocked 192 193 until the internal space overflows. Therefore, for movement mode 1, the external green time 194 before being blocked by the internal spillback is longer than the overlap time and equals to the 195 time needed to fill the internal space, which is expressed by the following formula:  $g_1 = \max\left(\frac{I'_L \cdot 3600 \cdot n}{q} - r\right), \frac{I'_L \cdot 3600 \cdot n}{s}\right)$ 196 (4) $g_1$  = green time of the external arterial before being blocked by the internal queue. 197 Since  $g_1$  could not be longer than the green time g, the formula (4) is adjusted to the 198 199 following:  $g_1 = \min(g, \max((\frac{I'/L \cdot 3600 \cdot n}{q} - r), \frac{I'/L \cdot 3600 \cdot n}{s}))$ 200 (5) 201 g = green time of the external arterial movement. During the time of  $g_1 - o$ , a platoon of vehicles in the internal space are discharged 202 through the downstream intersection, while the external traffic enters the internal space from the 203 upstream intersection. Therefore, the internal queue length at the end of  $g_1$  is 204  $Q_L = \max(0, I - \frac{(g_1 - o) \cdot s_d}{3600 \cdot n} \cdot L)$ 205 (6) $Q_L$  = the internal queue length at the end of  $g_1$ ; 206  $s_d$  = the saturated discharging traffic flow rate of the downstream intersection. 207 The time needed to discharge the internal queue  $Q_L$  is 208

With the changed values of the effective green time and v/c ratio of the external arterial through movement, the control delay calculation formulas documented in Chapter 16 of HCM 2000 are adjusted to reflect the actual control delay at diverging diamond interchanges.

According to the analysis in Section 2.1, the continuous green time of the external arterial through movement is divided into two separated effective green time (the second effective green time may be 0) due to the internal spillback. Thus, the uniform assuming uniform arrivals  $d_1$  is calculated using the following process:

If  $g_2 = 0$ , the green time g and v/c ratio X in the formula 16-11 in Chapter 16 of HCM 251 2000 are replaced by the effective green time g'and effective v/c ratio X'to get the following 252 formula:

253 
$$d_{1} = \frac{0.5C(1 - \frac{g}{C})^{2}}{1 - [\min(1, X')\frac{g'}{C}]} = \frac{0.5C(1 - \frac{g_{1}}{C})^{2}}{1 - [\min(1, X')\frac{g_{1}}{C}]}$$
(15)

 $d_1$  = the uniform delay. 254 255 Else The uniform arrival traffic flow is expressed by the following formula: 256  $q' = \min(q, c')$ 257 (16)q' = the uniform arrival traffic flow 258 259  $Q_1 = q' \cdot r$  $Q_1$  = the queue length of external arterial through movement at the beginning of 260 261 green time. If  $(r + g_1) \cdot q' \ge g_1 \cdot s$ , the external queue is not cleared at the end of  $g_1$ 262  $Q_2 = q' \cdot (r + g_1) - s \cdot g_1$ 263 (17) $Q_2$  = the external arterial queue length at the end of  $g_1$ . 264 265  $Q_3 = Q_2 + b \cdot q'$ (18) $Q_3$  = the external arterial queue length at the beginning of  $g_2$ . 266  $d_1 = (0.5 \cdot r \cdot Q_1 + 0.5 \cdot (Q_1 + Q_2) \cdot g_1 + 0.5 \cdot (Q_2 + Q_3) \cdot b$ (19)267  $+0.5 \cdot (\frac{(r+g_1+b) \cdot q'-s \cdot g_1}{S-a'})^2 \cdot s)/(C \cdot q')$ 268 Else, the external queue is cleared at the end of  $g_1$  $Q_{2} = 0$ 269  $Q_3 = Q_2 + b \cdot q'$ 270  $d_1 = 0.5 \cdot \frac{s \cdot r^2 + s \cdot b}{C \cdot (s - q')}$ 271 (20)If  $Q_3 > g_2 \cdot (s - q')$ , the external queue is not cleared at the end of  $g_2$ 272 Exchange values of *b* and *r*; 273 274 Exchange values of  $g_1$  and  $g_2$ ; 275  $d_1$  is calculated by formulas (17), (18) and (19).

276 277

278HCM 2000 are replaced by the effective green time g'and effective v/c ratio X' to develop the279following formulas to estimate the control delay:280
$$PF = \frac{(1-P)f_{PA}}{1-(\frac{B'}{C})}$$
281 $PF = the uniform delay progression adjustment factor, which accounts for effects282of signal progression.283 $P = the proportion of vehicles arriving of the external arterial movement on284green.285 $f_{PA} =$  supplemental adjustment factor for platoon arriving during green.286 $d_2 = 9007[(X'-1) + \sqrt{(X'-1)^2 + \frac{8klX'}{c'T}}]$ 287 $d_2 =$  incremental delay to account for the effect of random arrivals and288oversaturation queues, adjusted for the duration of the analysis period and type of289signal control; this delay component assumes that there is no initial queue for the290lane group at the start of the analysis period (s/veh);291 $T$  = analysis duration;292k = incremental delay factor that is dependent on controller settings;293l = upstream filtering/metering adjustment factor.294 $d_3 = \frac{1800Q_b(1+u)t}{c'T}$ 295 $d_3 =$  initial queue delay, which accounts for delay to all vehicles in the analysis296period due to initial queue at the start of the analysis period (s/veh);297 $Q_b =$  initial queue delay, which accounts for delay to all vehicles in the analysis298u = delay parameter;299t = 0 if  $Q_b = 0$ , else  $t = \min\{T, \frac{Q_b}{c'[1-\min(1,X')]}\}$ 301u = 0 if  $t < T$ , else  $u = 1 - \frac{c'T}{Q_b[1-\min(1,X')]}$ 302$$ 

The green time g and v/c ratio X in the formula 16-10, 16-12, F16-1 and 16-9 in Chapter 16 of



307 308

#### FIGURE 6 Flow chart of the control delay calculation for external movements.

The external movement calculation model is introduced here for application to the arterial 309 through movement. The off-ramp left turn movement in the advanced DDI configuration is the 310 other external movement impacted by the internal queue spillback. Delay of the left turn 311 312 movement can be calculated exactly following the steps for the arterial through movement 313 introduced above. The length of the queue left in the internal space at the end of the last phase,  $Q_{\scriptscriptstyle I\!L}$ , is the only parameter deserving more attention. The initial internal queue of the off-ramp 314 left turn movement is the residual internal queue from the arterial through movement, while the 315 residual queue from the off-ramp left turn movement is the initial internal queue of the arterial 316 317 through movement. Other external movements, with the exception of the arterial through

318 movement and the off-ramp left turn movement, are negligibly impacted by the internal queue 319 spillback, so they can be calculated with the model in Chapter 16 of HCM 2000.

320

# 321 **2.3 Movement Analysis and Control Delay Calculation for Internal Movements**

With different overlap time and different external movement modes, the downstream intersection has different signal progression, which is reflected by the Progression Adjustment Factor in the calculation model in Chapter 16 of HCM 2000. Good signal progression will result in a high proportion of vehicles arriving on the green. Poor signal progression will result in a low proportion of vehicles arriving on the red.

Based on the analysis and delay calculation of external movements, the internal control
 delay could be calculated by the following process:

356

357 358

359

360

361

362

363

364 365

366

367

368

369 370

371

372

373

374

375

376

377

378

379

380

381

FIGURE 7.

2000 by replacing *PF* with  $PF_{internal}$ .

**3 EXPERIMENTAL STUDY** 

 $d_{\text{internal}} = d_{1\text{internal}}(PF_{\text{internal}}) + d_{2\text{internal}} + d_{3\text{internal}}$ 

 $d_{\text{internal}}$  = the internal control delay;

 $d_{1 \text{int ernal}} = \text{the internal uniform delay;}$ 

 $d_{2internal}$  = the internal incremental delay;

 $d_{3internal}$  = the internal initial queue delay.

$$f_{PA} = \begin{cases} 1.00 , R_p \le 0.50 \\ 0.93 , 0.50 \le R_p \le 0.85 \\ 1.00 , 0.85 \le R_p \le 1.15 \\ 1.15 , 1.15 \le R_p \le 1.50 \\ 1.00 , 1.50 \le R_p \le 2.00 \\ 1.00 , 2.00 \le R_p \end{cases}$$
(32)  
$$f_{PA} = \text{supplemental adjustment factor for platoon arriving during green.}$$
(33)  
$$F_{F_{internal}} = \frac{(1-P) \cdot f_{PA}}{(1-\frac{g_{internal}}{C_{internal}})}$$
(33)  
$$PF_{internal} = \text{the uniform delay progression adjustment factor of the internal movement, which accounts for effects of signal progression;}$$

 $C_{\text{internal}}$  = the cycle length of the downstream intersection.

 $g_{\text{internal}}$  = the internal link through green time of downstream intersection;

The internal control delay can be calculated by the formula 16-9 in Chapter 16 of HCM

The flow chart of the internal control delay calculation model is demonstrated in

The internal left turn movement is not controlled by any signal. The movement is free

This section describes the test of effectiveness of the delay calculation model at diverging

with the common DDI lane design. Therefore, its control delay is not considered in this paper.

diamond interchanges. Owing to the difficulty of reproducing the studied cases in the field, we

used SimTraffic 7 simulation to develop the scenarios and validate the performance of the new

model. We chose simulation because field observation would be extremely difficult for this

research. It is very unlikely transportation agencies would allow us to try the overlap options in

the field. The simulation model used in the paper was previously developed for a research project

sponsored by the Texas Department of Transportation to evaluate the effectiveness of diamond

and X-pattern interchanges. It has been gone through vigorous calibration against field data (13).

1) representing respectively moderate and congested traffic conditions, to produce various

internal queue situations. The geometric design and hypothetical traffic demand profiles are from

Three scenarios were developed with three hypothetical traffic demand profiles (see Table

12

(34)

382 the paper of Edara, et al. (4). The hypothetical DDI layout and signal timing scheme are 383 demonstrated in Figure 8.



384	
385	

FIGURE 7 Flow chart of the control delay calculation for internal movements.

There are two on-ramps and two off-ramps that connect the arterial street and the freeway. The off-ramps have two left-turn lanes and one right-turn lane. Distance between the two crossovers is 500 ft. The arterial street has three through lanes and one right-turn lane for external traffic; one through and left-turn lane, and two through lanes for internal traffic. **TABLE 1 Hypothetical Traffic Demands** 

Traffic Demand	Northbound (veh/h)		Southbound (veh/h)			Eastbound (veh/h)			Westbound (veh/h)			
	L	Т	R	L	Т	R	L	Т	R	L	Т	R
Volume 1	700	0	400	700	0	400	400	800	500	400	800	500
Volume 2	800	0	500	800	0	500	500	900	600	500	900	600
Volume 3	1000	0	700	1000	0	700	700	1100	800	700	1100	800

391 392

Table 2 provides the data collected in the experimental study. Phase 1 traffic movement was affected by the internal queue spillback when the hypothetical traffic demand was Volume 3, the highest studied.

Control delay calculated by the conventional method in Chapter 16 of HCM 2000 is 74.1 seconds/vehicle, while the delay by the new method is 178.1 seconds/vehicle, which is much closer to the simulation value 148.7 seconds/vehicle. Figure 9 provides a more intuitive understand of how the calculated delay values by the new method are close to simulated ones.

400

V	<b>T</b> ·	T
XU.	LIU.	Tian
,	,	



Traffic Volume 1 Traffic Volume 2 Traffic Volume 3

# 407 FIGURE 9 Hypothetical DDI simulation model

# 4085 CONCLUSIONS

This study proposed a new analytical delay calculation model for diverging diamond interchanges (DDI). The performance of the new model was examined in traffic simulation and compared with the simulated control delay results. The analytical control delay calculation method, along with the detailed derivation of the formulas and the carefully designed calculation flow chart, would be helpful for researchers and practitioners to further study and effectively operate diverging diamond interchanges.

The proposed method in this paper is appropriate for the advanced DDI signal but not for the base DDI signal, because of the particularity of delay calculation of stop and yield control. In future research, control delay calculation of the base DDI signal phasing will be addressed by considering stop and yield control delay calculation in the proposed model.

The new approach has been approved to be effective for Tight Urban Diamond Interchanges and Diverging Diamond Interchanges. It also shows promise for use in other signalized interchange configurations with two or more adjacent intersections, which would be verified in the follow-up work.

423

# 424 ACKNOWLEDGEMENT

425 This work was supported in part by Natural Science Foundation of China (No.60974092)

## 426 **References**

- Tian, Z. Development and Evaluation of Operational Strategies for Providing an Integrated
   Diamond Interchange Ramp-Metering Control System. Ph.D. Dissertation, Department of Civil
   Engineering, Texas A&M University, College Station, Texas, May 2004.
- 430 2. Double Crossover Diamond Interchange, FHWA Publication No.: FHWA-HRT-09-054
- 431
  431
  3. Chlewicki, G. New Interchange and Intersection Designs: The Synchronized Split-Phasing
  432
  433
  433
  434
  435
  435
  435
  436
  436
  436
  437
  438
  439
  439
  430
  430
  430
  430
  430
  430
  431
  431
  432
  433
  433
  433
  434
  434
  435
  435
  436
  436
  437
  438
  438
  438
  439
  439
  430
  430
  430
  430
  430
  430
  430
  430
  431
  431
  432
  432
  433
  433
  434
  434
  435
  435
  436
  437
  437
  438
  438
  438
  439
  439
  430
  430
  430
  430
  430
  430
  430
  430
  430
  430
  430
  431
  431
  431
  432
  432
  433
  433
  433
  434
  434
  435
  435
  436
  437
  437
  438
  438
  438
  439
  439
  439
  430
  430
  430
  430
  431
  431
  431
  432
  432
  433
  433
  434
  434
  434
  435
  435
  436
  436
  437
  438
  438
  438
  439
  439
  439
  430
  430
  431
  431
  431
  432
  433
  433
  434
  434
  434
  434
  434
  435
  435
  436
  436
  436
  437
  438
  438
  438
  439
  439
  439
  439
  4
- 434
   4. Edara, Praveen K, Bared, JoeG and Jagannathan, Ramanujan, Diverging Diamond Interchange 435
   4. Edara, Praveen K, Bared, JoeG and Jagannathan, Ramanujan, Diverging Diamond Interchange and Double Crossover Intersection-Vehicle and Pedestrian Performance.
- 436
  5. Beckmann, M.J., C.B. McGuire, and C.B. Winsten. Studies in the Economics of Transportation.
  437
  437 New Haven, Yale University Press, 1956.
- 438
  6. Webster, F.V. Traffic Signal Settings, Road Research Lab, Technical Paper No. 39. Her Majesty
  439 Stationary Office, London, England, 1958.
- van Zuylen, H. J., and F. Viti. Delay at controlled intersections: the old theory revised.
  Proceedings of the IEEE ITSC 2006, 2006 IEEE Intelligent Transportation Systems
  Conference, Toronto, Canada, September 17-20, 2006.
- 8. TRB, 2000. Highway Capacity Manual, special report 209. National Research Council,
  Washington D.C., TRB, 2000.
- Fambro, D. B., and N. M. Rouphail. Generalized Delay Model for Signalized Intersections and Arterial Streets. Transportation research record No. 1572, Highway Capacity Issues and Analysis, 1997.
- 448 10. Fambro, D. B., and C. J. Messer. Estimating Delay at Coordinated Signalized Intersections,
  449 Proceedings of the International Symposium on Highway Capacity, Karlsruhe, A. A. Balkema,
  450 Rotterdam, 1991, pp. 127-143.
- 451
   451
   452
   452
   453
   453
   11. Elefteriadou, L., F. C. Fang and E. Prassas. A Methodology for Evaluating The Operational Performance of Interchange Ramp Terminals. Transportation Research Record, 2005, Vol. 1920, pp. 13-24.
- 454
   12. Xu, H., H. Liu and Z. Tian. Control Delay at Signalized Diamond Interchanges Considering
   455
   456
   12. Xu, H., H. Liu and Z. Tian. Control Delay at Signalized Diamond Interchanges Considering
   456
   456
   456
   456
- 457
  458
  458
  458
  459
  13. Liu, H., H, Xu, and P. R. Evuri. Comprehensive Evaluation of Diamond and X-Pattern Interchanges Using Vissim Simulation. TechMRT Research Report 0012-2008, Texas Tech University Multidisciplinary Research Center in Transportation.