DETERMINING QUAD GATE OPERATION TIMES UTILIZING TRAFFIC SIMULATION OF SHOCK WAVE AT HIGHWAY-RAIL INTERSECTIONS

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Abstract: The concept of dynamic dilemma zone based on vehicle speed reduction on approach to highway-rail intersections was developed by Moon (1998) to aid in refining four quadrant gate operating times. The methodology based on analytical methods was employed on single vehicle and three-vehicle platoons with short and long headways. Four quadrant gate operation times were improved relative to earlier Coleman and Moon (1996) development efforts. However, the randomness of traffic flow parameters, such as speed, headways, and vehicle mix, and the likelihood of fixed four quadrant gate operating parameters lead to development of stochastic dynamic dilemma zone simulation model to develop four quadrant gate operating parameters. Shock wave of the lead car and car-following theory are used within the dynamic dilemma zone approach to model driver-vehicle behavior in platoons. Findings suggest that traffic flow conditions yield four quadrant gate operating times in the 5 – 7 second range.

Key Words: Dynamic Dilemma Zone, Highway-Rail Intersections, Four Quadrant Gates, Shock Wave Model, Car-Following Model, Traffic Simulation, Gate Delay, Gate Interval Time

1. INTRODUCTION

Moon (1998) developed the concept of a dynamic dilemma zone (DDZ) whose length is a function of vehicle speed profiles and driver behavior at highway-rail intersections. A dynamic dilemma zone as opposed to a static dilemma zone is a road segment on approach to an intersection which varies in length based on fluctuations in vehicle speeds and the number of vehicles within a road segment. This is in contrast to a static dilemma zone which is based on a constant approach speed and single vehicle in the road segment. Moon established that a dynamic dilemma zone exists and can be modeled through shock wave and car-following theory to model driver-vehicle parameters in this zone.

Coleman and Moon (1996) determined gate operation time building on the analogy of a static dilemma zone from research on traffic signal change intervals which assures that a very high percentage of drivers will clear the intersection or stop before entering. Similar to the highway-highway intersection, Coleman and Moon utilized a constant speed on the approach to the highway-rail intersection. However, since entrapment is the concern, Coleman and Moon determined a constant minimum speed through the highway-rail intersection to address entrapment. This is less of a concern in the highway-highway case since the expectation is to clear the intersection unimpeded during the change interval. Using their modification to the yellow clearance interval methodology with a constant minimum speed in the highway-rail intersection area, data from six sites in Illinois yielded gate interval times in the range of 14 - 22 seconds. These high values led to the conclusion that crossing violations after near gate arms have been lowered would be likely.

Moon and Coleman (1999) determined that drivers reduced their speed on approach to highway-rail intersections. The inclusion of a dynamic dilemma zone in algorithms to determine four quadrant gate operating parameters was conducted leading to revised estimates of gate delay and gate interval times. Utilizing field data in the DDZ methodology, Moon (1998) obtained the gate operation times, *i.e.* gate delay and gate interval time with different number of vehicles in a platoon. It was concluded that 8.90 seconds of gate delay for the Hartford site and 8.10 seconds of gate delay for the McLean site would be required in order to minimize the dynamic dilemma zone during gate delay and to reduce the possibility of a vehicle hitting the entry gate. In addition, 4.80 seconds of gate interval time for the Hartford site and 4.00 seconds of gate interval time for the McLean site were required to ensure a safe system operation to minimize the possibility of a vehicle becoming "trapped" between the entry and the exit gates.

Four quadrant gate operation times were improved relative to earlier Coleman and Moon (1996) development efforts. However, these values were obtained under limited platoon size and without inherent randomness in speed of vehicles, headways, and acceleration (deceleration) rate. This means that the gate delay and gate interval time values are approximate for the known conditions. A modeling approach is needed to accommodate a range and randomness of those variables and to yield more insight. Since traffic flow variables and vehicle mix is a random and variable set of conditions four quadrant gate operating parameters are likely to be fixed but must accommodate the range of traffic flow conditions under which they will operate. The initial experiment is to determine capacity profile of the highway-rail intersection areas to identify a bottleneck zone, i.e. the track zone. Shock waves of the lead vehicle in a platoon needs to be found to originate at the bottleneck zone under different flow and density relationships which explain and quantify temporal speed variations due to phenomena of highway-rail intersections. In addition, car following model needs to be developed as a function of sensitivity, stimuli, and moving shock wave of initial acceleration/deceleration conditions in a platoon.

A computer simulation technique is implemented, that includes stochastic characteristics and mathematical models that describe the behavior of such variables in order to determine gate delay and gate interval time for four-quadrant gate system at highway-rail intersections.

This paper utilizes the concept of a dynamic dilemma zone road segment. The determination of the dynamic dilemma zone aids in defining the conditions which contribute to the likelihood of vehicle clearance (or stopping) at four quadrant gate highway-rail intersections. A simulation model incorporating field data, determination of a dynamic dilemma zone, and algorithms to determine gate operation times is demonstrated for the development of quad gate operation times.

2. DETERMINING GATE OPERATION TIMES

2.1 Summary of Field Data

Moon and Coleman (1999) collected speed data as a component of driver behavior at two sites where four quadrant gates are under consideration in the Chicago-St. Louis high-speed passenger rail corridor.

Table 1 provides a summary of the data collection and reduction on separate days in October 1996 at the two sites of Hartford and McLean. The time period of data collection at Hartford had three hours (one hour AM and two hours PM) for the stopping distance and the track zones. For McLean two hours PM data were collected for the stopping distance and the track zones. Table 2 shows the summary of data collected on separate days in July 1997 at the same sites. Four hours of data (two hours AM and PM each) were collected at the Hartford site. Three hours data (one hour AM and two hours PM) were collected at the McLean site.

Table 1. Summary of Data Collection and Reduction (Oct. 1996)

Approach Type	Single Vehicles				Platoons			
Site Name	Hartford		McLean		Hartford		McLean	
Time Period (hr)	AM (1)	PM (2)	AM (2)	PM	AM (1)	PM (2)	AM (2)	PM
Data Group	A	B	C	-	D	E	F	-
Direction	WB	WB	EB	-	WB	WB	EB	-
No. of Cases	80	185	108	-	31	86	21	-
No. of Vehicles	80	185	108	-	73	254	48	-
Vehicle Types								
Autos	56	141	66		56	187	34	
Trucks	24	44	40		17	66	14	
SU[a]	15	36	21		11	56	7	
WB-12[b]	9	8	19		6	10	7	
School Buses	0	0	2		0	1	0	

[a] Single Unit Truck, AASHTO Definition
[b] Semi-Trailer Intermediate, AASHTO Definition

Table 2. Summary of Data Collection and Reduction (Jul. 1997)

Approach Type	Single Vehicles				Platoons			
Site Name	Hartford		McLean		Hartford		McLean	
Time Period	AM	PM	AM	PM	AM	PM	AM	PM
(hr)	(2)	(2)	(1)	(2)	(2)	(2)	(1)	(2)
Data Group	G	H	I	J	K	L	M	N
Direction	WB	WB	EB	WB	WB	WB	EB	WB
No. of Cases	142	200	81	138	64	60	13	49
No. of Vehicles	142	200	81	138	172	157	32	106
Vehicle Types								
Autos	74	137	53	80	96	95	21	67
Trucks	68	63	28	58	76	62	11	39
SU[a]	33	40	21	35	39	29	6	31
WB-12[b]	35	23	7	23	37	33	5	8
School Buses	0	0	0	0	0	0	0	0

[a] Single Unit Truck, AASHTO Definition
[b] Semi-Trailer Intermediate, AASHTO Definition

At McLean four pavement markings were used for reference location and/or distance for east and west bound traffic. The first and the second reference locations were marked at 93 meters (300 ft) and 31 meters (100 ft) from the entry gate, respectively. The third marker was the entry gate and the fourth was the exit gate. Thus there exist three zones: Zone A, B, and C. Zone A is a highway segment between the first and the second reference marker, which is 62 meters (200 ft) long. Zone B is 31 meters (100 ft) long between the second reference marker and the entry gate. The distance between the entry and exit gates is called Zone C which is 14 meters (46 ft) long.

At Hartford four reference markers were set for location and/or distance for west bound traffic. For the east bound there was not an adequate location for the camera to capture a good view of the intersection approach and the track zone due to several buildings on both sides of the highway. The first reference location was marked at 77 meters (250 ft) from the entry gate. However the second reference location was marked at 31 meters (100 ft) from the entry gate, similar to the McLean site. The third and the fourth markers were the entry and the exit gate, respectively. Three zones were developed as: Zone A, B, and C. Zone A is a highway segment between the first and the second reference marker, which is 46 meters (150 ft) long. Zone B is 31 meters (100 ft) long between the second reference marker to the entry gate. The track distance between the entry and exit gates is called Zone C which is 26 meters (85 ft) long.

2.2 Simulation Approach for Dynamic Dilemma Zone Estimation

Computer simulation models have been used widely in the analysis and assessment of the highway transportation system, examples include traffic capacity analysis, traffic stream models, car-following and shock wave models, queueing analysis for signalized and/or unsignalized intersections. May (1990) defined simulation as a numerical technique for conducting experiments on a digital computer, which may include stochastic characteristics, be microscopic or macroscopic in nature, and involve mathematical models that describe the behavior of a transportation system over extended periods of real time.

The major objective for incorporating simulation models in this paper is to utilize dynamic dilemma zone methodology with important stochastic elements that will define four quadrant gate parameters under a wide range of operational conditions. These elements were collected from the sites so that they are compatible with simulation model requirements. The Hartford site field data with four data groups of single vehicles and corresponding four data groups of platoons are used as the main data sources for Hartford. Three data groups of single vehicles and corresponding three data groups of platoons are used as data sources for the simulation model of McLean.

Table 3 shows the size of the platoons from the field data for two sites: Hartford and McLean. Most of the platoons have two or three vehicles.

Table 3. Size of the Platoon for Hartford and McLean Sites

Site Data Group (No. of platoons)	2 vehicles	3 vehicles	4 vehicles	5 vehicles	more than 5 vehicles
Hartford					
Group D (31)	22	8	0	1	0
Group E (86)	52	15	7	6	6
Group K (64)	39	10	11	4	0
Group L (60)	45	6	4	1	4
McLean					
Group F (21)	16	4	1	0	0
Group M (13)	7	6	0	0	0
Group N (49)	42	6	1	0	0

Speed and deceleration rates from the data group of single vehicles are inputs in the simulation model in order to generate vehicles under free flow conditions. For platoons headway data from the data groups of platoons is utilized as the interarrival time for generating vehicles in order to develop the car-following logic in the simulation model. The attribute assignments for input variables based on data collection and reduction are indicated in Table 4 for Hartford site and in Table 5 for McLean site. Statistical tests were conducted on field data of speeds, deceleration rates, and headway to determine if they are from either a normal distribution or a lognormal distribution. Based on chi-square test, the measured speed distribution for Zone A, B, and C is found to be statistically representative of the normal distribution. The measured headway distribution is also found to be statistically representative of the normal distribution. However, the measured deceleration distribution for Zone AB and Zone BC is found to be statistically representative of the lognormal distribution. Perception-reaction times from a study of brake reaction times of unalerted drivers by Taoka (1989) are applied for calculating the safe stopping distance.

Table 4. Attribute Assignments for Input Variables at Hartford Site

Input Variables	Distribution	Parameters (Mean, Std Dev)	Reference
Approach Speed, m/s	Normal Dist.	(19.98, 2.69)	Data Group A
		(18.01, 4.65)	Data Group B
		(18.78, 3.41)	Data Group G
		(19.01, 3.68)	Data Group H
Deceleration Rate for Zone AB, m/s^2	Lognormal Dist.	(0.76, 0.27)	Data Group A
		(0.46, 0.55)	Data Group B
		(0.68, 0.36)	Data Group G
		(0.60, 0.32)	Data Group H
Deceleration Rate for Zone BC, m/s^2	Lognormal Dist.	(0.95, 0.40)	Data Group A
		(0.83, 0.53)	Data Group B
		(0.76, 0.45)	Data Group G
		(0.88, 0.48)	Data Group H
Perception Reaction Time, sec	Lognormal Dist.	(1.30, 0.60)	Taoka (1989)
Headway (Interarrival Time), sec	Normal Dist.	(2.47, 1.09)	Data Group D
		(2.37, 1.00)	Data Group E
		(2.58, 0.96)	Data Group K
		(2.48, 0.99)	Data Group L

Table 5. Attribute Assignments for Input Variables at McLean Site

Input Variables	Distribution	Parameters (Mean, Std Dev)	Reference
Approach Speed, m/s	Normal Dist.	(17.26, 2.82)	Data Group C
		(17.41, 3.34)	Data Group I
		(17.06, 2.59)	Data Group J
Deceleration Rate for Zone AB, m/s^2	Lognormal Dist.	(0.52, 0.32)	Data Group C
		(0.55, 0.30)	Data Group I
		(0.45, 0.20)	Data Group J
Deceleration Rate for Zone BC, m/s^2	Lognormal Dist.	(1.16, 0.59)	Data Group C
		(1.26, 0.61)	Data Group I
		(1.16, 0.49)	Data Group J
Perception Reaction Time, sec	Lognormal Dist.	(1.30, 0.60)	Taoka (1989)
Headway (Interarrival Time), sec	Normal Dist.	(2.81, 1.30)	Data Group F
		(3.16, 1.32)	Data Group M
		(3.21, 1.11)	Data Group N

The simulation model for dynamic dilemma zone contains three modules: (1) vehicle creation (single or platoon) and attribute assignment, (2) calculation of dynamic dilemma zone based on shock wave and car-following situations, and (3) data collection including gate operation times. A simulation package, AWESIM® by Pritsker, *et al.* (1997) is utilized to build these modules. Initially the vehicle creation and attribute assignment process is developed using AWESIM® network. This includes global variables related to the site geometry and platoon characteristics such as size of the platoon. The second module is controlled externally through user-written programs to control the behavior of drivers in a platoon based on attribute assignments in the previous module. Visual C++ is used to code the program. In the third module, outputs are made including microscopic speed profiles for each vehicle in a platoon, dynamic dilemma zone, and the gate operation times.

The final procedure is validation. The validity and accuracy of the proposed simulation model needs to be tested by comparing with field data. A comparison of simulation output speeds with field data of platoon(s) speed is conducted by calculating microscopic car-following speed for each vehicle in a platoon, *i.e.* the lead, the second, the third, and so on. Benekohal (1991) suggested a method of comparing speed profiles graphically for validation of microscopic traffic flow simulation models for long distance (about a half mile) of highway. However, the distances covered in this study for highway-rail intersections are relatively short, and therefore an average speed for such a short distance in each zone will be used. In addition, a comparison of simulation output headways with field data of platoon headways is conducted by calculating the average headway for vehicles in a platoon. Group B data of single vehicles is used as input for Hartford site in order to generate vehicles under free flow conditions. The simulation model generates car-following speed profiles for platoons based on lead vehicle speeds and their shock waves, which are expected to be less than those under free flow conditions. For validation at Hartford site the average speed of this output is compared with the platoons speed of Group E data set, which are less than the single vehicles speed profiles of Group B based on the data analysis conducted by Moon and Coleman (1999). Also the average headway of the output is compared with the platoons headway of Group E data set. For the validation at McLean site Group C and F data sets are used. In the validation procedure the output includes gate operation times by minimizing the dynamic dilemma zone.

If the proposed simulation model is valid the final gate operation times are determined by minimizing the dynamic dilemma zone utilizing unused data groups in the simulation model. Groups D, K, and L are used as input for Hartford site to generate inter-arrival times for vehicles in a platoon using their time headway. Groups A, G, and H for single vehicles are utilized as input for Hartford site to assign the variables of speed and acceleration (deceleration) rate under free flow conditions to the generated vehicles. Four sets of gate operation times are obtained utilizing Groups D&A, K&G, and L&H, as well as E&B for the purpose of validation.

For McLean site, groups M and N are utilized as input to generate inter-arrival vehicles in a platoon by headway. Groups I and J are utilized to assign the variables of speed and acceleration (deceleration) rate under free flow conditions to the generated vehicles. Three sets of gate operation times are obtained utilizing M&I and N&J as well as F&C for the purpose of validation.

2.3 Validating Simulation Model by Comparing Average Speed with Field Data

Tables 6 and 7 show the average value of microscopic speed profiles in a platoon from the simulation runs using 15 replications with different random number seeds compared to field measurement of vehicle speed in platoons. For the Hartford site, 5 vehicles are generated in a platoon in order to simulate the speed profiles of those vehicles. This is because the size of 80 platoons of 86 total from Group E data set is less than or equal to 5 vehicles. For McLean site 3 vehicles are generated in order to compare average speeds from Group F data set in which the size of platoon is less than or equal to 3 vehicles for 20 of 21 platoons total.

A t test is performed to examine the statistical significance of the difference in average speed calculation. The t statistic is used for estimating difference between means of two samples with degrees of freedom (sample size or number of simulation runs) ranging from 1 through 30.

The hypothesis is that the average speed in each zone from the simulation runs is equal to that from field data, *i.e.* H_0: $\mu = \mu_0$.

The t statistic is calculated according to $t(n\text{-}1)$ distribution as following:

$$t = \frac{\overline{X} - \mu_o}{s/\sqrt{n}} \qquad (1)$$

As shown in Table 6 the computed t values for the lead vehicle of a platoon in each zone based on 15 replications are less then the tabular value, $t_{\alpha=0.05}(14)$ = 2.1448. Thus the hypothesis is not rejected. This means there is no statistically significant difference in the average speed of lead vehicles in platoons between field data and the simulation data.

Table 6. Comparison of Simulated Speeds for the Lead Vehicle at Hartford Site

Lead Car	Speed: Zone A	Speed: Zone B	Speed Zone C
Average Field Speed (m/s) (n = 86)	18.33	15.83	12.45
Simulation Speed (m/s) 15 replications			
No. 1	18.74	17.74	15.97
No. 2	18.17	17.01	15.18
No. 3	17.29	15.23	13.05
No. 4	15.93	12.86	7.57
No. 5	24.01	22.22	18.93
No. 6	16.24	13.92	10.53
No. 7	20.24	18.90	17.04
No. 8	18.06	16.96	15.58
No. 9	20.39	18.87	16.82
No. 10	22.67	21.83	20.79
No. 11	15.27	12.20	7.50
No. 12	16.25	13.78	8.46
No. 13	15.48	13.74	11.36
No. 14	16.97	12.90	7.40
No. 15	12.23	10.59	7.47
Average	17.86	15.92	12.91
Std. Dev.	3.02	3.51	4.61
Difference	0.47	- 0.09	- 0.46
t value	0.5782	0.0924	0.3731
$t_{\alpha=0.05}(14)$	2.1448	2.1448	2.1448

(Note) Zone A: highway segment between the 2 markers at 77 and 31 meters from the entry gate;
Zone B: highway segment between the marker at 31 meters and the entry gate; and
Zone C: highway segment between the entry gate and the exit gate.

Table 7 is for the following vehicles, 2nd, 3rd, 4th, and 5th. The results indicate that there is no statistically significant difference in average speeds for the following vehicles.

Table 7. Comparison of Simulated Speeds for the following Vehicles at Hartford Site

Vehicle in Platoon		Speed: Zone A	Speed: Zone B	Speed Zone C
2nd Vehicle	Average Field Speed (m/s)	16.68	14.82	11.59
(n = 86)	Simulation Speed (m/s)			
	15 replications			
	Average	16.76	14.22	12.61
	Std. Dev.	2.75	4.03	4.64
	Difference	0.10	0.60	1.02
	t value	0.1396	0.5610	0.8185
3rd Vehicle	Average Field Speed (m/s)	16.19	13.87	10.89
(n = 34)	Simulation Speed (m/s)			
	15 replications			
	Average	15.55	13.24	12.55
	Std. Dev.	3.27	4.53	4.64
	Difference	0.64	0.63	- 1.66
	t value	0.7367	0.5218	1.3388
4th Vehicle	Average Field Speed (m/s)	15.78	13.75	10.43
(n = 19)	Simulation Speed (m/s)			
	15 replications			
	Average	14.34	12.82	12.54
	Std. Dev.	4.13	4.71	4.63
	Difference	1.44	0.93	- 2.11
	t value	1.3030	0.7399	1.7017
5th Vehicle	Average Field Speed (m/s)	15.46	13.25	10.02
(n = 12)	Simulation Speed (m/s)			
	15 replications			
	Average	13.81	12.70	12.53
	Std. Dev.	4.42	4.71	4.63
	Difference	1.65	0.55	- 2.51
	t value	1.3949	0.4340	2.0288
	$t_{\alpha=0.05}(14)$	2.1448	2.1448	2.1448

As shown in Table 7 the computed t values for the 2^{nd}, 3^{rd}, 4^{th}, and 5^{th} vehicles in the platoon in each zone based on 15 replications are less then the tabular values. Thus the hypothesis that the average speed of the vehicles in a platoon in each zone from the simulation runs is not statistically different from the field data is not rejected.

Based on the results on comparison of average speeds between field data and the simulated output it is concluded that there is no significant difference in average speeds for vehicles in platoons at the Hartford site. This means the simulation model is valid for representing the average speed of vehicles in the dynamic dilemma zone methodology including shock waves and car-following logic.

Table 8 shows the comparison of simulated speed in each zone with those from the field data (Group F data set) at McLean site.

As shown in Table 8 the computed t values for vehicles in platoon in each zone based on 15 replications are less then the tabular value, $t_{\alpha=0.05}(14) = 2.1448$. Thus the hypothesis is not rejected. This means there is no statistically significant difference in the average speed for lead vehicles in platoons between field data and the simulation data.

Table 8. Comparison of Simulated Speeds for the Lead Vehicle at McLean Site

	Vehicle in Platoon	Speed: Zone A	Speed: Zone B	Speed Zone C
Lead	Average Field Speed (m/s)	15.97	13.60	10.11
Vehicle	Simulation Speed (m/s)			
($n = 21$)	15 replications			
	Average	15.73	14.73	11.06
	Std. Dev.	2.85	2.62	3.87
	Difference	0.24	- 1.13	- 0.95
	t value	0.3139	1.6108	0.9175
2nd Vehicle	Average Field Speed (m/s)	14.37	12.07	9.28
($n = 21$)	Simulation Speed (m/s)			
	15 replications			
	Average	15.54	13.00	10.70
	Std. Dev.	2.67	3.49	3.87
	Difference	- 1.17	- 0.93	- 1.42
	t value	1.6375	0.9993	1.3692
3rd Vehicle	Average Field Speed (m/s)	12.94	11.20	8.80
($n = 5$)	Simulation Speed (m/s)			
	15 replications			
	Average	14.42	11.44	10.51
	Std. Dev.	2.75	3.91	3.85
	Difference	- 1.48	- 0.24	- 1.71
	t value	2.0084	0.2324	1.6617
	$t_{\alpha=0.05}(14)$	2.1448	2.1448	2.1448

(Note) Zone A: highway segment between the 2 markers at 93 and 31 meters from the entry gate;
Zone B: highway segment between the marker at 31 meters and the entry gate; and
Zone C: highway segment between the entry gate and the exit gate.

Based on the results on comparison of average speeds between field data and the simulated output it is concluded that there is no statistically significant difference in average speeds for vehicles in platoons at the McLean site.

2.4 Simulation Results for Determining Gate Delay and Gate Interval Time

Utilizing different sets of field data as input in the validated simulation model the gate operation times, *i.e.* gate delay and gate interval time are determined as shown in Table 9 at Hartford site and Table 10 at McLean site. Table 9 shows consistent results from the simulation runs using 15 replications with different random number seeds. Group E&B is used in the validation, however the remaining groups are not. A conclusion is that 6.60 seconds of gate delay would be required at Hartford site in order to minimize the dynamic dilemma zone during gate delay and to eliminate the possibility of a vehicle hitting the entry gate. In addition, 6.30 seconds of gate interval time is required to ensure a safe system operation in terms of eliminating the possibility of a vehicle becoming "trapped" between the entry and the exit gates.

Table 9. Simulation Results of Gate Delay and Gate Interval Time at Hartford Site

Data Group by Time and Date	Gate Delay (sec)	Gate Interval Time (sec)
Group D&A (AM, Oct. 1996)	6.60	6.20
Group E&B (PM, Oct. 1996)	6.10	6.20
Group K&G (AM, Jul. 1997)	6.30	6.30
Group L&H (PM, Jul. 1997)	6.30	6.30

The results from the simulation runs using 15 replications with different random number seeds are consistent at McLean site as shown in Table 10. Group F&C is used in the validation, however the remaining groups are not. A conclusion is that 6.10 seconds of gate delay would be required at McLean site in order to minimize the dynamic dilemma zone during gate delay and to eliminate the possibility of a vehicle hitting the entry gate. Moreover, 4.90 seconds of gate interval time is required to ensure a safe system operation in terms of eliminating the possibility of a vehicle becoming "trapped" between the entry and the exit gates.

Table 10. Simulation Results of Gate Delay and Gate Interval Time at McLean Site

Data Group by Time and Date	Gate Delay (sec)	Gate Interval Time (sec)
Group F&C (AM, Oct. 1996)	6.10	4.80
Group M&I (AM, Jul. 1997)	6.10	4.90
Group N&J (PM, Jul. 1997)	6.00	4.80

3. CONCLUSIONS

Utilizing all groups of field data as input in the validated simulation model the gate operation times, *i.e.* gate delay and gate interval time are obtained using 15 replications with different random number seeds. A conclusion is that 6.60 seconds of gate delay for the Hartford site and 6.10 seconds of gate delay for the McLean site would be required in order to minimize the dynamic dilemma zone during gate delay and to diminish the possibility of a vehicle hitting the entry gate. In addition, 6.30 seconds of gate interval time for the Hartford site and 4.90 seconds of gate interval time for the McLean site are required to ensure a safe system operation to minimize the possibility of a vehicle becoming "trapped" between the entry and the exit gates.

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