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차량추종 모델과 운전자 행태에 근거한 철도교차로의 동적 딜레마 구간

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Car-Following and Dynamic Dilemma Zone Model for Determining Gate Operation Times Based on Driver Behavior at Highway-Rail Intersections

Ph.D Thesis
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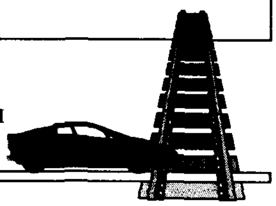
Advisor: Fred Coleman, III
CE/UIUC, 1997



MyJ 1

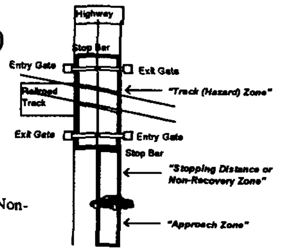
Outline

- Introduction
- Coleman & Moon Methodology for Designing Four Quad-Gate (QG) Operation Times
- Driver Behavior at Highway-Rail Intersections
- Development of New Methodology
  - Dynamic Dilemma Zone (DDZ) and Car-Following (CF)
  - Data Collection and Reduction
  - Field Data Analysis for Vehicular Speed Profiles
  - Simulation & Validation for DDZ Estimation
  - Optimal Gate Operation Times
- Conclusions and Recommendations

MyJ 2

1 Introduction

- Four Quadrant Gate (QG) at Highway-Rail Intersections (HRI)
  - Gates
    - Entry Gate
    - Exit Gate
  - Zones
    - Approach Zone
    - Stopping Distance or Non-Recovery Zone
    - Track or Hazard Zone



MyJ 3

Introduction

- Determining Gate Operation Times
  - Coleman & Moon (TRR 1553, 1997)
  - Gate Delay, T_D using Dilemma Zone Concept
    - From Research on Traffic Signal Intersections
    - Single Vehicle and Constant Speed Approach
  - Gate Interval Time, T_I
    - Using Predetermined Constant Minimum Speed
      - Higher Range of Interval Time (14 - 22 sec)
      - Possibility of Crossing Violation during T_I

MyJ 4

Problem Statement

- Assumptions on Static Dilemma Zone
  - Single Vehicle
  - Constant Speed Approach
- Questions?
  - Platoon Approach
  - Speed Variation
  - Gate Operation Parameters

MyJ 5

Problem Statement

- Factors affecting Gate Operation Times
  - Driver Behavior:
    - Stopping, Clearance, and Continuation Distance
    - Approach Speed, Perception-Reaction Time (PRT), Accel/Decel Rates
  - Geometry:
    - Width: No. of Railroad Tracks, App. Highway Lanes
    - Distance between Stop Bar and Gate
  - Others:
    - Warning Devices, Roughness, Obstacles, etc.

MyJ 6

Objectives

- Dynamic Dilemma Zone (DDZ) Model
  - Existence
  - By Car-Following Logic at HRI
- QG Operating Parameters
  - Minimize the risk of trapping a vehicle between the entry and exit gates
- Driver Behavior at HRI
  - Speed Profiles, Accel/Decel Rates, and Headway
    - Using Data Collection and Analysis
    - Input for a simulation model to DDZ

MyJ 7

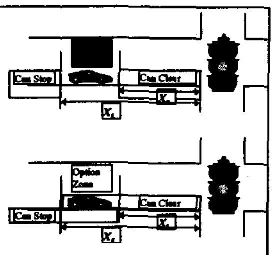
2 Design of QG Operation Times

- Gate Operation Times
  - Gate Delay
    - Interval between initiation of flashing light and the entry gate arm descent
    - 3 seconds (MUTCD), 3 - 5 seconds (IDOT)
  - Gate Interval Time
    - Interval between initiation of the entry and exit gates descent
    - 1 - 3 sec min. (LRT), 3 - 5 sec (NYSDOT)
  - Coleman & Moon (*TRR 1553*, 1997)
    - Design Approach by Dilemma Zone Concept

MyJ 8

Dilemma Zone Concept

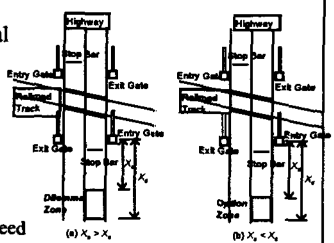
- Application to Highway-Highway Intersections (HHI)
- The Dilemma:
  - The drivers' decision ***to proceed*** through the intersection or ***to stop*** when the signal changes from green to yellow



MyJ 9

Dilemma Zones at HRI

- Similarity to HHI
- Drivers Use Visual Signal
  - Flashing Lights
  - Gates
    - Quad Gates
    - Dual Gates
- Decision Making
  - To stop or to proceed
  - Dilemma Zone



MyJ 10

Distance Variables

- Stopping Distance (X_s)

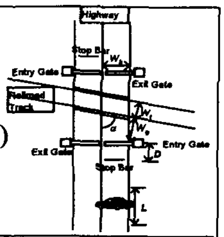
$$X_s = \Delta T \cdot v + \frac{v^2}{[illegible]} + D$$

- Continuation Distance (X_c)

[illegible]

- Clearance Distance (X_{clr})

[illegible]



$$W_{ghi} = \frac{W_T}{\sin\alpha} + \frac{2 \cdot W_E}{\tan\alpha} + \frac{2 \cdot W_E}{\sin\alpha}, \quad \alpha \le 90^\circ$$
$$= \frac{W_T}{[illegible]} + \frac{2 \cdot W_E}{[illegible]} + \frac{2 \cdot W_E}{[illegible]}, \quad \alpha > 90^\circ$$

MyJ 11

Safe Decision Location

- $X_s = X_c$: Safe Decision Location
  - Both dilemma and option zones are eliminated
  - A point or distance is obtained which assures the likelihood of drivers stopping or clearing the intersection
  - $X_s > X > X_c$: Dilemma Zone
  - $X_s < X < X_c$: Option Zone
- This gives:

$$T_G = \left\{\Delta T + \frac{v}{[illegible]} + \frac{D}{[illegible]}\right\} + \left\{\frac{1}{[illegible]}(W_{ghi} - L)\right\}.$$

MyJ 12

QG Operation Times

- Gate Operation Time: T_G
  - Gate Delay, T_D
  - Gate Interval Time, T_I

$$T_G = T_D + T_I,$$

$$T_D = \left\{ \Delta T + \frac{v}{2(d + G \cdot g)} + \frac{D}{v} \right\},$$

$$T_I = \left\{ \frac{1}{v} (W_{ght} + L) \right\}$$

MyJ 13

Findings for Six Intersections

- Gate Delay

Street of the Intersection, City	Approach Speed, kph (mph)	Gate Delay at ΔT (PRT) = 1	Gate delay at ΔT (PRT) = 2.5
U.S. Route 136, McLean	72 (45)	4.5	6.0
N. Grand Ave., Springfield	56 (35)	3.7	5.2
Hawthorn St., Hartford	64 (40)	4.1	5.6
Main St., Gardner	56 (35)	3.7	5.2
Main St., Pontiac	40 (25)	3.1	4.6
Trunk Route 35A, Chenoa	40 (25)	3.1	4.6

- Gate Interval Time

Street of the Intersection, City	Min. Spd in Track Zone, kph (mph)	Gate Interval for Auto	Gate Interval for Truck
U.S. Route 136, McLean	8 (5)	8.9	15.1
N. Grand Ave., Springfield	8 (5)	14.3	20.5
Hawthorn St., Hartford	8 (5)	14.7	21.1
Main St., Gardner	5 (3)	11.4	21.9
Main St., Pontiac	5 (3)	11.8	22.3
Trunk Route 35A, Chenoa	8 (5)	7.0	13.3

MyJ 14

3 Driver Behavior at HRI

- Probability of Crossing
  - Meeker and Barr (1989), Meeker et al. (1997)
  - As a function of train location, train speed, time available until train arrival
  - A significant percentage of drivers made a decision to cross the intersection during activation of the flashing lights
- Head Movements
  - Sanders (1976), Aberg (1988), Tenkink and Horst (1988)
  - *Performed Action: Head Movements, Lowering Windows,* Reducing Speed
  - Fewer head movements at higher speed of vehicles

MyJ 15

Driver Behavior at HRI

- Speed Reduction
  - Shinar and Raz (1982)
    - Observations: 200 and 80 meters from the track (no trains)
    - Most drivers reduced speed under 5 different protection conditions
  - Meeker et al. (1997)
    - 60 drivers under two different protection conditions
    - Driver behavior at train's approaching

Driver Behavior	Flashing Lights Only	Gates and Flashing Lights
Cross despite Warning	39 of 58 (67%)	23 of 60 (38%)
Stop before Proceeding	14 of 39 (36%)	4 of 23 (17%)
Slow before Proceeding	20 of 39 (51%)	7 of 23 (30%)
Did not Stop or Slow	5 of 39 (13%)	12 of 23 (52%)

  - Summary: Drivers reduced their approach speed most at intersections regardless of trains approaching

MyJ 16

Speed Reduction as a Key Factor

- Intergreen Interval at HHI
  - Chang et al. (1985), Horst and Wilmink (1986)
  - The duration of yellow is dependent on vehicle speed
  - Shortcomings: constant speed of single vehicle
- Gate Operation Times at HRI
  - Coleman and Moon (1997)
  - Different assumption on speed profile at HHI
  - *Constant speed approach for gate delay*
  - Critical min. speed at track zone for gate interval
- Speed Reduction as a Key Variable to Represent Driver Behavior at HRI

MyJ 17

4 New Methodology

- Dynamic Method for Defining Variables
  - Speed Variation $v(t) = v(t-1) + T[a(t-1) + a(t)]$
  - Vehicle Location $x(t) = x(t-1) + T[v(t-1) + v(t)]$
  - Stopping Dist. $X_s(t') = \Delta T \cdot v(t') + \frac{v^2(t')}{\cdots} + D$
  - Clearance Dist. $X_{cl} = \frac{T}{2}[v(0) + v(1)] + \frac{T}{2}[v(1) + v(2)] + \cdots + \frac{T}{2}[v(T_D - 1) + v(T_D)] = T \sum^{T_D} [v(t-1) + v(t)]$
  - Continuation Dist. $X_c(t') = T \sum^{T_D} [v(t-1) + v(t)]$

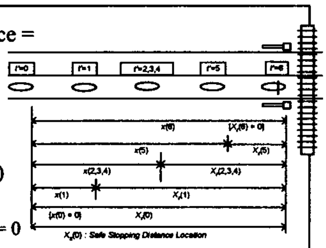
MyJ 18

Remaining Distance

- Remaining Distance = Safe Stopping Dist. - Vehicle Location

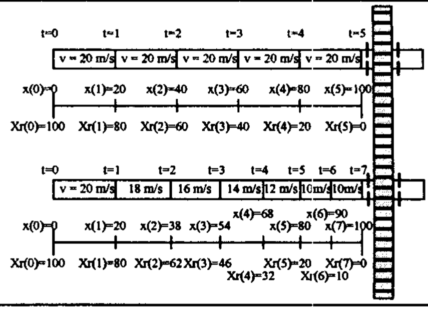
  $X_r(t') = X_s(0) - x(t')$

- $x(0) = 0, x(T_D) = X_s(0)$
- $X_r(0) = X_s(0), X_r(T_D) = 0$



MyJ 19

Remaining Dist. Vs. Vehicle Location



MyJ 20

Dynamic Dilemma Zone (DDZ)

- DDZ = Remaining Dist. - Continuation Dist.
  - ***DDZ*** $= X_r(t') - X_c(t')$, for $t' = 0, 1, \ldots, T_D$
  - Eliminating Dynamic Dilemma Zone at any t'
  - At $t' = 0$, Remaining Dist. = Safe Stopping Dist.
- \- Optimal Gate Operation Times
  - Min. DDZ for Constant Speed Approach
  - Min. DDZ for Speed Reduction

$$\begin{aligned} &Max \quad T_G = T_D + T_I \\ &s.t. \quad X_c(t') = X_r(t') \le X_s, \quad t' = 0, 1, \ldots, T_D \end{aligned}$$

MyJ 21

DDZ for Constant Speed

- Constant Speed over time t'
  - $v(t') = v$, $a(t') = 0$, for $t' = 0, 1, \ldots, T_D$
- DDZ for Const Spd $X_c(t') = v \cdot (T_D - t'), \quad t' = 0, 1, \cdots, T_D$

  $$\begin{aligned} X_r(t') &= X_s(0) - x(t') \\ &= X_s - (t' \cdot v), \quad t' = 0, 1, \cdots, T_D \end{aligned}$$

- Optimal Gate Delay (= Coleman&Moon Method)

$$\begin{aligned} T_D &= \frac{1}{v} \cdot X_s = \frac{1}{v} \cdot \left\{ \Delta T \cdot v + \frac{v^2}{2 \cdot (a + G \cdot g)} + D \right\} \\ &= \Delta T + \frac{v}{2 \cdot (a + G \cdot g)} + \frac{D}{v} \end{aligned}$$

MyJ 22

DDZ for Constant Speed

- Optimal Gate Interval Time
  - $X_{clr} = T_G \cdot v = (T_D + T_I)\, v$
  - $X_{clr} = X_s + (W_{ght} + L)$
  - thus, $(T_D + T_I)\, v = X_s + (W_{ght} + L)$
  - This gives

$$T_I = \frac{1}{v} \cdot (W_{ght} + L)$$

  \- Identical to Coleman&Moon Method

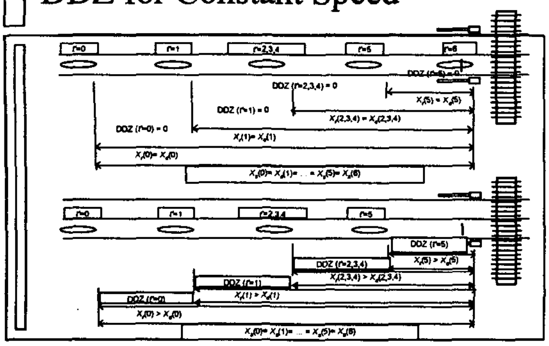
MyJ 23

DDZ for Constant Speed

	T_D = 6 sec Based on eq. (4.10)	T_D = 5 sec	T_D = 7 sec
Assumptions			
Approach Speed, v	21 m/s	21 m/s	21 m/s
PRT	2.5 sec	2.5 sec	2.5 sec
Typical Decel., d	3.0 m/s²	3.0 m/s²	3.0 m/s²
Stopp. Distance, X_s	126 meter	126 meter	126 meter
Track Width	42 meter	42 meter	42 meter
Dynamic Dilemma Zone	$DDZ = X_r - X_c$	$DDZ = X_r - X_c$	$DDZ = X_r - X_c$
t' = 0 sec.	0 = 126 – 126	21 = 126 – 105	-21 = 126 – 147
t' = 1 sec.	0 = 105 – 105	21 = 105 – 84	-21 = 105 – 126
t' = 2 sec.	0 = 84 – 84	21 = 84 – 63	-21 = 84 – 105
t' = 3 sec.	0 = 63 – 63	21 = 63 – 42	-21 = 63 – 84
t' = 4 sec.	0 = 42 – 42	21 = 42 – 21	-21 = 42 – 63
t' = 5 sec.	0 = 21 – 21	21 = 21 – 0	-21 = 21 – 42
t' = 6 sec.	0 = 0 – 0		-21 = 0 – 21
	Mimimized Dynamic Dilemma Zone	Dynamic Dilemma Zone	Dynamic Option Zone
Gate Interval Calculation			
Track Zone Speed	21 m/s	*The vehicle may hit*	21 m/s
T_I	2.0 seconds	*the entry gate.*	2.0 seconds

MyJ 24

DDZ for Constant Speed



DDZ for Speed Reduction

- Speed Reduction over time t'
  - $v(0) = v$, $a(t') = a$ (constant decel.), $t' = 0, 1, \ldots, T_D$
  - $v(t') = v(t' - 1) + a$
  - $x(t') = t' \cdot v + t'^2/2 \cdot a$
  - $X_r(t') = X_s - x(t') = X_s - t' \cdot v - t'^2/2 \cdot a$
  - $X_c(t') = X_c(t' - 1) - \{v + a\,(2\,t' - 1)/2\}$
- At $t' = T_D$
  - $X_r(T_D) = X_s - x(T_D) = X_s - T_D \cdot v - T_D^2/2 \cdot a$
  - $X_c(T_D) = 0$
  - $X_r(T_D) = X_c(T_D)$

DDZ for Speed Reduction

- Optimal Gate Delay $T_D = -\frac{v}{a} \pm \sqrt{\left(\frac{v}{a}\right)^2 + \frac{2 \cdot X_s}{a}}$.
- Optimal Gate Interval Time
  - By $T_I = \frac{(W_{ghi} + L)}{v(T_D)}$,
  - Then

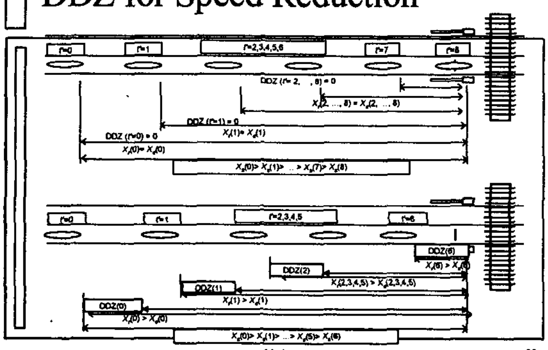
$$T_I = -\frac{(v + T_D \cdot a)}{a} \pm \sqrt{\left(\frac{v + T_D \cdot a}{a}\right)^2 + \frac{2 \cdot (W_{ghi} + L)}{a}}$$

$$= -\frac{v(T_D)}{a} \pm \sqrt{\left(\frac{v(T_D)}{a}\right)^2 + \frac{2 \cdot (W_{ghi} + L)}{a}}.$$

DDZ for Speed Reduction

	T_D = 8 sec Based on eq. (4.13)	T_D = 6 sec By Table 4.1
Assumptions		
Approach Speed, v	21 m/s	21 m/s
Deceleration Rate, a	− 1.31 m/s²	− 1.31 m/s²
Safe Stopping Distance, X_s	126 meter	126 meter
Track Width, $W_{ghi}+L$	42 meter	42 meter
Dynamic Dilemma Zone	$DDZ = X_r - X_c$	$DDZ = X_r - X_c$
t' = 0 sec.	0 = 126.08 − 126.08	23.66 = 126.08 − 102.42
t' = 1 sec.	0 = 105.73 − 105.73	23.66 = 105.73 − 82.07
t' = 2 sec.	0 = 86.70 − 86.70	23.66 = 86.70 − 63.04
t' = 3 sec.	0 = 68.97 − 68.97	23.66 = 68.97 − 45.31
t' = 4 sec.	0 = 52.56 − 52.56	23.66 = 52.56 − 28.90
t' = 5 sec.	0 = 37.45 − 37.45	23.66 = 37.45 − 13.79
t' = 6 sec.	0 = 23.66 − 23.66	23.66 = 23.66 − 0.0
t' = 7 sec.	0 = 11.17 − 11.17	
t' = 8 sec.	0 = 0 − 0	
	Minimized Dynamic Dilemma Zone	Dynamic Dilemma Zone
Gate Interval Calculation		
Speed at $t' = T_D$	10.52 m/s	*The vehicle may hit the entry gate.*
For a = 0.0 m/s², T_I	4.0 seconds	
For a = − 1.31 m/s², T_I	7.5 seconds	

DDZ for Speed Reduction



Car-Following DDZ

- 5th GM Model

$$\ddot{x}_{n+1}(t+1) = \frac{1.0 \cdot [\dot{x}_{n+1}(t+1)]}{[x_n(t) - x_{n+1}(t)]}[\dot{x}_n(t) - \dot{x}_{n+1}(t)] \quad \text{(Acceleration/Deceleration)}$$

$$\dot{x}_{n+1}(t) = \dot{x}_{n+1}(t-1) + \frac{T}{2}[\ddot{x}_{n+1}(t-1) + \ddot{x}_{n+1}(t)] \quad \text{(Speed)}$$

$$x_{n+1}(t) = x_{n+1}(t-1) + \frac{T}{}[\dot{x}_{n+1}(t-1) + \dot{x}_{n+1}(t)] \quad \text{(Distance)}$$

- Stopping Dist. $X_{s,n+1}(t') = \Delta T \cdot \dot{x}_{n+1}(t') + \frac{\dot{x}^2_{n+1}(t')}{\ldots} + D$
- Continuation Dist. $X_{c,n+1}(t') = \frac{T}{} \sum^{T_D} [\dot{x}_{n+1}(t-1) + \dot{x}_{n+1}(t)]$
- Remaining Dist.

Car-Following DDZ

- $DDZ = X_{r,n+1}(t') - X_{s,n+1}(t')$, for $t' = 0, 1, \ldots, T_D$

$$X_{c,n+1}(t') < X_{r,n+1}(t') < X_{s,n+1}(t')$$
$$\textit{where}, \quad X_{r,n+1}(t') = X_{s,n+1}(0) - x_{n+1}(t'), \quad t' = 0, 1, \ldots, T_D.$$

- Optimal Gate Operation Times

$$\textit{Max} \quad T_G = T_D + T_I$$
$$\textit{s.t.} \quad X_{c,n+1}(t') = X_{r,n+1}(t') < X_{s,n+1}(t'), \quad t' = 0, 1, \ldots, T_D.$$

MyJ 31

Data Collection and Reduction

- Site Selection
  - Vehicle Arresting Barrier (VAB) Installation
    - Hartford, McLean, and Chenoa Sites
  - Considering AADT for Car-Following
  - Two Sites: Hartford and McLean
- Data Collection
  - Single day in Oct. 1996 & in Jul. 1997 for each site
    - weather: partly cloudy
    - morning (2 hrs) and afternoon (2 hrs)
  - Video Camera
    - viewing area: about 100 - 130 meters (300 - 400 ft)

MyJ 32

Data Collection and Reduction

- Reference Points
  - Hartford: 77 and 31 meters from the entry gate
    - Zone A: 46 meters long (from 77 to 31 meters)
    - Zone B: 31 meters long (from 31 meters to the entry gate)
    - Zone C: 26 meters long (from the entry to the exit gates)
  - McLean: 93 and 31 meters from the entry gate
    - Zone A: 62 meters long (from 93 to 31 meters)
    - Zone B: 31 meters long (from 31 meters to the entry gate)
    - Zone C: 14 meters long (from the entry to the exit gates)
- Camera Location:
  - A good view of approach zone and the track zone

MyJ 33

Data Collection and Reduction

- Sample Size
  - If 100 speed data are collected
    - 4.25 m/s of std. dev. and
    - 1.00 m/s permissible error
    - 95% confidence

$$N = \left(\frac{t_{\alpha/2} \cdot s}{e}\right)^2 = \left(\frac{1.96 \, x \, 4.25}{1.00}\right)^2 \cong 70$$

- Grouping of Data
  - Single vs. Platoon
  - Weber-Fechner Relationship
    - average 10 m/s of speed in the track zone
    - 4.6 meters of buffer dist. (B) recommended
    - **average 4.6 sec of headway**

$$h = \Delta t + \frac{(L+B)}{v}$$

MyJ 34

Data Collection and Reduction

- Data Reduction
  - Time Unit: 1 sec (collection) ⇨ 1/30 sec (reduction)
  - Video Tape Recorder ⇨ Spreadsheet (MS Excel)
  - Manual data recording method instead of image processing technique
- Getting the values
  - Speed = dist. / veh. travel time for each section
  - Accel (decel) rate = speed variation between two sections / travel time for these two sections
  - Headway = interarrival time of vehicles

MyJ 35

Data Collection and Reduction

- Summary of Data 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	234	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	

  - Jul. 1997

Approach Type	Single Vehicles				Platoons			
Site Name	*Hartford*		*McLean*		*Hartford*		*McLean*	
Time Period (hr)	AM (2)	PM (2)	AM (1)	PM (2)	AM (2)	PM (2)	AM (1)	PM (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

MyJ 36

Vehicular Speed Profiles for Field Data at HRI

- Microscopic Speed Profiles
  - A Primary Factor in the Designing and Controlling Traffic Performance on Highway
  - Estimate DDZ and Car-Following at HRI
- Two Groups for Speed Profiles
  - Single Vehicles
  - Platoon of Vehicles
    - By the Time Headway
    - Two Sites: Hartford and McLean

Testing Speed Reduction

- Using Single Vehicles Data
  - Between Approach Zones: Zone A, B, and C
  - Hartford: (Oct. 1996 Group A & B), (Jul. 1997 Group G & H
  - McLean: (Oct. 1996 Group C), (Jul. 1997 Group I and J)
- Assumption
  - H_0: Two sets of speed are equal
  - Zone A and B (H_0: μ_A - μ_B = 0)
  - Zone B and C (H_0: μ_A - μ_B = 0)
  - Standard deviation of the difference of the means

$$\hat{s}_{AB} = \sqrt{\left(\frac{s_A^2}{n_A} + \frac{s_B^2}{n_B}\right)}$$

$$\hat{s}_{BC} = \sqrt{\left(\frac{s_B^2}{n_B} + \frac{s_C^2}{n_C}\right)}$$

Testing Speed Reduction

- Group A:
  - Test between Zone A and Zone B
    - $\mu_A - \mu_B = 3.16$ m/s > 2*0.44: at $\alpha = 0.95$
      - Reject H_o and "Significant difference between A & B"
      - Definite tendency to reduce speed from Zone A to Zone B
  - Test between Zone B and Zone C
    - $\mu_A - \mu_B = 3.70$ m/s > 2*0.40: at $\alpha = 0.95$
      - Reject H_o and "Significant difference between B & C"
      - Definite tendency to reduce speed from Zone B to Zone C

Test Results: Hartford

	Zone A & B	Zone B & C
Group A (AM, Oct. 1996)		
Mean Difference (m/s)	3.16	3.70
Std. Dev. Difference (m/s)	0.44	0.45
95 % Interval (m/s)	0.88	0.90
Speed Variation	YES	YES
Group B (PM, Oct. 1996)		
Mean Difference (m/s)	1.79	3.20
Std. Dev. Difference (m/s)	0.44	0.38
95 % Interval (m/s)	0.88	0.76
Speed Variation	YES	YES
Group G (AM, Jul. 1997)		
Mean Difference (m/s)	3.33	3.31
Std. Dev. Difference (m/s)	0.42	0.41
95 % Interval (m/s)	0.84	0.82
Speed Variation	YES	YES
Group H (PM, Jul. 1997)		
Mean Difference (m/s)	2.92	3.53
Std. Dev. Difference (m/s)	0.39	0.39
95 % Interval (m/s)	0.78	0.78
Speed Variation	YES	YES

Speed Profiles for Single Vehicle

- Microscopic Speed Characteristics in Each Zone
  - Normal Distribution for the Speed Profiles
    - Zone A, B, and C
    - Utilized as input distribution for simulation
  - Chi-square Test
    - Hypothesis: the measured distribution is identical to the normal distribution
  - Estimation of size of the class interval by Sturges (1926)

$$I = \frac{Range}{}$$

Deceleration Rate: Single Veh.

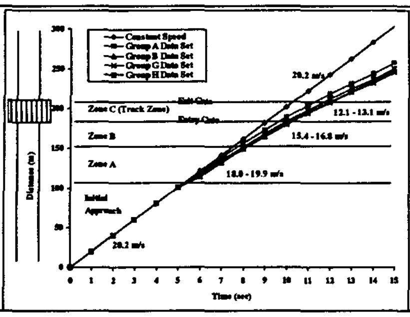
- Based on Speed Reduction

$$t_{AB} = \frac{v_A - v_B}{}$$

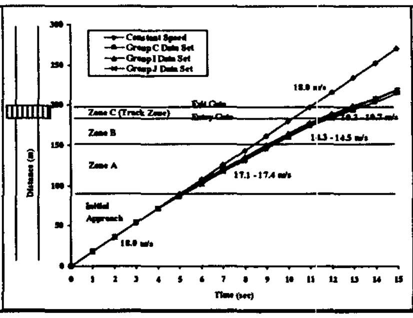
- Chi-square Test: Lognormal Distribution

	Deceleration Rates (m/s^2) Between Zone A and Zone B		Deceleration Rates (m/s^2) Between Zone B and Zone C	
Data Set	Mean	Std. Dev.	Mean	Std. Dev.
Hartford				
Group A	0.76	0.27	0.95	0.40
Group B	0.46	0.55	0.83	0.53
Group G	0.68	0.36	0.76	0.45
Group H	0.60	0.32	0.88	0.48
McLean				
Group C	0.52	0.32	1.16	0.59
Group I	0.55	0.30	1.26	0.61
Group J	0.45	0.20	1.16	0.49

Single Veh. Speed: Hartford



Single Veh. Speed: McLean



Platoon Vs. Single Vehicles

- Testing Speed Difference between Platoon and Single Vehicles
  - Hartford: Group (A vs. D), (B vs. E), (G vs. K), (H vs.L)
  - McLean: Group (C vs. F), (I vs. M), (J vs. N)
  - Assumption
    - Two sets of speed are equal
    - for Group (A vs. D)
      - Zone A: (H_o: $\mu_{A(A)} - \mu_{A(D)} = 0$)
      - Zone B : (H_o: $\mu_{B(A)} - \mu_{B(D)} = 0$)
      - Zone C: (H_o: $\mu_{C(A)} - \mu_{C(D)} = 0$)

$$\hat{s}_{A(DA)} = \sqrt{\left(\frac{s^2_{A(D)}}{n_{A(D)}} + \frac{s^2_{A(A)}}{n_{A(A)}}\right)}$$

$$\hat{s}_{B(DA)} = \sqrt{\left(\frac{s^2_{B(D)}}{n_{B(D)}} + \frac{s^2_{B(A)}}{n_{B(A)}}\right)}$$

$$\hat{s}_{C(DA)} = \sqrt{\left(\frac{s^2_{C(D)}}{n_{C(D)}} + \frac{s^2_{C(A)}}{n_{C(A)}}\right)}$$

Test Results: Hartford

	Zone A	Zone B	Zone C
Group D&A (AM, Oct. 1996)			
Mean Difference (m/s)	0.95	1.32	1.05
Std. Dev. Difference (m/s)	0.46	0.52	0.46
95 % Interval (m/s)	0.92	1.04	0.92
Speed Difference	YES	YES	YES
Group E&B (PM, Oct. 1996)			
Mean Difference (m/s)	1.06	1.52	1.55
Std. Dev. Difference (m/s)	0.40	0.35	0.32
95 % Interval (m/s)	0.80	0.70	0.64
Speed Difference	YES	YES	YES
Group K&G (AM, Jul. 1997)			
Mean Difference (m/s)	2.28	1.80	1.42
Std. Dev. Difference (m/s)	0.36	0.39	0.36
95 % Interval (m/s)	0.72	0.78	0.72
Speed Difference	YES	YES	YES
Group L&H (PM, Jul. 1997)			
Mean Difference (m/s)	1.52	1.64	1.22
Std. Dev. Difference (m/s)	0.34	0.38	0.35
95 % Interval (m/s)	0.68	0.76	0.70
Speed Difference	YES	YES	YES

Speed Profiles for Platoons

- Platoon Size for Hartford and McLean

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

- Headway Characteristics: Hartford
  - Chi-square Test: Normal Distribution

Platoon Speed Profiles: Hartford

	Zone A	Zone B	Zone C
Group D (AM, Oct. 1996): 31 Platoons	(mean, std. dev)	(mean, std. dev)	(mean, std. dev)
1st vehicle (31 veh.), m/s	(19.39, 2.92)	(16.15, 3.22)	(12.51, 3.31)
2nd vehicle (31 veh.), m/s	(18.81, 2.95)	(15.23, 3.32)	(12.11, 2.77)
3rd vehicle (9 veh.), m/s	(17.94, 2.98)	(13.90, 3.23)	(10.35, 2.06)
4th vehicle (1 veh.), m/s	(20.78, 0.00)	(16.04, 0.00)	(11.43, 0.00)
5th vehicle (1 veh.), m/s	(22.96, 0.00)	(17.58, 0.00)	(13.40, 0.00)
Group E (PM, Oct. 1996): 86 Platoons	(mean, std. dev)	(mean, std. dev)	(mean, std. dev)
1st vehicle (86 veh.), m/s	(18.33, 3.25)	(15.83, 3.39)	(12.45, 3.28)
2nd vehicle (86 veh.), m/s	(16.86, 3.34)	(14.82, 3.44)	(11.59, 3.03)
3rd vehicle (34 veh.), m/s	(16.19, 2.72)	(13.87, 3.33)	(10.89, 2.68)
4th vehicle (19 veh.), m/s	(15.78, 2.13)	(13.75, 2.71)	(10.43, 2.60)
5th vehicle (12 veh.), m/s	(15.46, 1.70)	(13.25, 2.95)	(10.02, 2.14)
Group K (AM, Jul. 1997): 64 Platoons	(mean, std. dev)	(mean, std. dev)	(mean, std. dev)
1st vehicle (64 veh.), m/s	(17.00, 2.60)	(14.52, 2.70)	(11.37, 3.05)
2nd vehicle (64 veh.), m/s	(16.85, 2.79)	(13.92, 3.23)	(10.98, 2.98)
3rd vehicle (25 veh.), m/s	(15.44, 3.36)	(11.87, 3.74)	(9.34, 2.75)
4th vehicle (15 veh.), m/s	(14.89, 2.72)	(11.91, 3.30)	(9.43, 2.66)
5th vehicle (4 veh.), m/s	(15.36, 4.65)	(12.90, 4.08)	(9.65, 3.71)
Group L (PM, Jul. 1997): 60 Platoons	(mean, std. dev)	(mean, std. dev)	(mean, std. dev)
1st vehicle (60 veh.), m/s	(18.16, 2.91)	(15.11, 3.28)	(11.80, 3.13)
2nd vehicle (60 veh.), m/s	(17.40, 2.73)	(14.28, 3.06)	(11.29, 2.90)
3rd vehicle (15 veh.), m/s	(16.13, 2.71)	(13.15, 3.41)	(10.71, 3.12)
4th vehicle (9 veh.), m/s	(16.11, 2.83)	(13.66, 3.49)	(10.66, 2.56)
5th vehicle (5 veh.), m/s	(17.54, 0.29)	(14.64, 2.14)	(10.98, 0.69)

Summary of Speed Data Analysis

- Speed Variation (Reduction)
  - Using single vehicles and platoons for two sites
  - Definite tendency to reduce speed
- Comparison bet. Platoon Vs. Single Veh.
  - Platoon speeds are less than single vehicles'
  - In platoon, average speed of following vehicles are less than that of the leading vehicles
- Input for Simulation
  - Speed profiles, decel. rates, and headway

MyJ 49

DDZ Estimation for Single Veh.

- Assumptions
  - a train may approach at any time, the interaction between a vehicle and a train can occur
  - a single "average vehicle approaches the crossing at t = 0 sec
    - interacts at and within the stopping distance area with a train
- Stopping Distance

	At PRT = 1 sec From AASHTO (1990)	At PRT = 1.8 sec From Taoka (1989) (85th percentile)	At PRT = 2.5 sec From AASHTO (1990)
Stopping Distance (m) Gate Delay Needs (sec)	77.75 4.2 (=77.75/18.60)	92.63 5.0 (=92.63/18.60)	105.65 5.7 (=105.65/18.60)
Variables Used Approach Speed Typical Decel. Rate Grade of Crossing	 18.60 m/s (61.02 ft/s) 3.05 m/s² (10 ft/s²) 0 %	 18.60 m/s (61.02 ft/s) 3.05 m/s² (10 ft/s²) 0 %	 18.60 m/s (61.02 ft/s) 3.05 m/s² (10 ft/s²) 0 %

MyJ 50

DDZ Estimation for Single Veh.

- DDZ calculation without speed reduction
  - Hartford: by Coleman&Moon methodology
    - DDZ is minimized: T_D = 5.70 sec, T_I = 2.50 sec

Time (sec)	Accel. (m/s²)	Speed (m/s)	Vehicle Posit.(m)	Stopping Dist. (m)	Continuat. Dist. (m)	Remaining Dist. (m)	DDZ (m)
0.00	0.00	18.60	0.00	105.65	106.02	105.65	0.37
1.00	0.00	18.60	18.60	105.65	87.42	87.05	0.37
2.00	0.00	18.60	37.20	105.65	68.82	68.45	0.37
3.00	0.00	18.60	55.80	105.65	50.22	49.85	0.37
4.00	0.00	18.60	74.40	105.65	31.62	31.25	0.37
5.00	0.00	18.60	93.00	105.65	13.02	12.65	0.37
5.60	0.00	18.60	104.16	105.65	1.86	1.49	0.37
5.70	0.00	18.60	**106.02**				
7.00	0.00	18.60	130.20				
8.20	0.00	18.60	**152.52**				

MyJ 51

DDZ Estimation for Single Veh.

- DDZ with Speed Reduction (Coleman&Moon)

Time (sec)	Accel. (m/s²)	Speed (m/s)	Vehicle Posit.(m)	Stopping Dist. (m)	Continuat. Dist. (m)	Remaining Dist. (m)	DDZ (m)
0.00	- 0.55	18.60	0.00	105.65	97.22	105.65	8.44
1.00	- 0.55	18.05	18.30	100.97	78.87	87.36	8.49
2.00	- 0.55	17.50	36.05	96.39	61.06	69.61	8.55
3.00	- 0.55	16.95	53.24	91.91	43.81	52.41	8.60
4.00	- 0.55	16.40	69.89	87.53	27.11	35.76	8.66
5.00	- 0.85	15.85	85.99	83.25	10.96	19.67	8.71
5.60	- 0.85	15.42	95.36	79.93	1.54	10.30	8.75
5.70	- 0.85	15.33	**96.89**				
7.00	- 0.85	14.23	116.05				
9.70	- 0.85	11.93	**151.24**				

- Gate Delay = 5.70 sec.
- Gate Interval Time = 4.00 sec
- DDZ is **not** minimized

MyJ 52

DDZ Estimation for Single Veh

- DDZ with Speed Reduction

Time (sec)	Accel. (m/s²)	Speed (m/s)	Vehicle Posit.(m)	Stopping Dist. (m)	Continuat. Dist. (m)	Remaining Dist. (m)	DDZ (m)
0.00	- 0.55	18.60	0.00	105.65	106.29	105.65	0.64
1.00	- 0.55	18.05	18.30	100.97	87.94	87.36	0.58
2.00	- 0.55	17.50	36.05	96.39	70.13	69.61	0.52
3.00	- 0.55	16.95	53.24	91.91	52.88	52.41	0.47
4.00	- 0.55	16.40	69.89	87.53	36.18	35.76	0.42
5.00	- 0.85	15.85	85.99	83.25	20.03	19.67	0.36
6.20	- 0.85	14.91	104.43	76.12	1.49	1.22	0.27
6.30	- 0.85	14.82	**105.91**				
7.00	- 0.85	14.23	116.05				
9.70	- 0.85	11.93	**151.24**				

- Gate Delay = 6.30 sec.
- Gate Interval Time = 3.40 sec
- DDZ is minimized

MyJ 53

Car-Following DDZ Estimation

- Assumption
  - Last veh. of a platoon is located at the stopping distance zone when a train is approaching
  - Two vehicles in a platoon
    - LV = the lead vehicle
    - TV = the target vehicle (i.e. the last vehicle)
  - Three vehicles in a platoon
    - LV = the lead vehicle
    - FL = the following vehicle (i.e. the intermediate vehicle)
    - TV = the target vehicle (i.e. the last vehicle)

MyJ 54

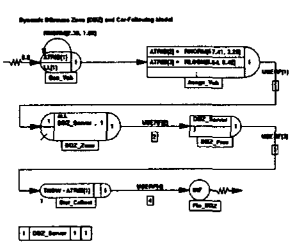
Car-Following DDZ Estimation

	Single Veh. (const. Spd)	Single Veh. (Spd. Redu.)	Platoon of 2 Long Hdwy	Platoon of 2 Short Hdwy	Platoon of 3 Long Hdwy	Platoon of 3 Short Hdwy
Target Veh.			2nd Veh	2nd Veh.	3rd Veh.	3rd Veh.
Speed ($t=0$)						
LV			17.30 m/s	18.00 m/s	14.90 m/s	17.30 m/s
FV					17.30 m/s	18.00 m/s
TV	18.60 m/s	18.60 m/s	18.90 m/s	18.90 m/s	18.90 m/s	18.90 m/s
Headway						
LV:FV			44.98 m	25.52 m	44.98 m	25.51 m
FV:TV					44.98 m	25.52 m
Accel. Rate						
LV	0.00 m/s^2	-0.55 m/s^2	-0.86 m/s^2	-0.64 m/s^2	-0.86 m/s^2	-0.86 m/s^2
Speed ($t=T_D$)						
LV			10.85 m/s	12.32 m/s	13.70 m/s	11.54 m/s
FV					13.51 m/s	11.40 m/s
TV	18.60 m/s	14.82 m/s	10.95 m/s	12.43 m/s	13.32 m/s	11.24 m/s
Speed ($t=T_I$)						
LV			13.86 m/s	12.58 m/s	16.45 m/s	14.63 m/s
FV					16.26 m/s	14.53 m/s
TV	18.60 m/s	11.93 m/s	13.76 m/s	12.47 m/s	16.06 m/s	14.42 m/s
Min. DDZ	0.37 m	0.27 m	0.41 m	0.14 m	0.15 m	0.29 m
Gate Delay	5.70 sec	6.30 sec	7.50 sec	6.90 sec	8.20 sec	7.40 sec
Gate Interval	2.50 sec	3.40 sec	3.80 sec	4.00 sec	3.30 sec	3.60 sec

Simulation for DDZ Estimation

- Objectives
  - Identify DDZ based on car-following logic including stochastic elements of variables
  - 4 Groups at Hartford (1 Group for Validation, Group B & E)
  - 3 Groups at McLean (1 Group for Validation, Group C & F)
- Software: AWESIM and Visual C++
- Input Variables
  - Speed: Normal Dist. using single vehicles for free flow conditions
  - Deceleration Rates: Lognormal Dist.
  - Headway: Normal Dist.
  - PRT: Lognormal Dist. (from Taoka, 1989)

AWESIM Network



Simulation Control Functions

```
;AweSim Control 1.0
;
;------ CONTROL PROGRAM ------
;
;Dynamic Dilemma Zone and Car Following Simulation
;
GEN,"Young J. Moon","DDZ and CF Model",4/25/1997,15,YES,YES;
INITIALIZE,0.0,3600.,YES;
LIMITS,12,5,-1,5,2;
RECORD,,,TNOW,"TIME",{AWESIM},,TTBEG,TTFIN;
REPORT,,YES,YES,EVERY(1),{{ALL,2}};
;
;Global Variables
;LL(1) = Maximum No. of Vehicles Generated
;LL(2) = Target Vehicle Number
;XX(1) = Time Increment dT (sec)
;XX(2) = Sensitivity Parameter (alpha_0)
;XX(3) = Speed Limit for This Site (m/s)
;XX(4) = Typical Deceleration Rate (m/s/s)
;XX(5) = Approach Distance (m)
;XX(6) = Distance between Entry and Exit Gates (m)
;XX(7) = Deceleration Rates without Brakes (m/s/s)
;XX(8) = 15th% speed for lead veh on the track zone (m/s)
;XX(9) = 15th% speed for following veh. on track zone (m/s)
;XX(10) = Maximum Time for Calculation (sec)
;
INTLC,{{XX[1],0.1},{XX[2],29.8},{XX[3],10.06},{XX[4],3.1},{XX[5],150.}};
INTLC,{{XX[6],46.78},{XX[7],0.0},{XX[8],9.12},{XX[9],7.63},{XX[10],360.}};
INTLC,{{LL[1],5},{LL[2],5}};
;
NETWORK,READ;
SIMULATE;
FIN;
```


User Insert Program: Visual C++

```
/* USERF Subroutines for DDZ/CF System -- Ph.D. Model by Young Moon */

#include "vslam.h"
#include <stdio.h>
#include <math.h>

int  iOpen = 0, i, j;
long nG = 0, nTarget, nT_Target;
double Time_Pre_Gen = 0.;

double Speed_Veh[1200][5000], Accel_Veh[1200][5000], Posit_Veh[1200][5000],
       Hdwy_Dist[1200][5000], Travel_Time[1200];

double Dist_Stop[1200][5000], Dist_Cont[1200][5000], Dist_Appl, Dist_Half,
       Dist_Remg[1200][5000], Dist_Totl, Dist_Appr, Dist_Crit[1200],
       Dist_Dilm[5000], Dist_Diff[5000], Gate_Delay, Gate_Intvl;

double Time_Trvl[1200], Time_Rete[1200][3], dT, Time_Min_Diff;

double SWFUNC USERF (int iCode, ENTITY*peUser)
{ double dReturn = 0.;

  double Time_Car_Gen, Pr_Stopp, Posit_Veh_0, Dist_Cont_0, Time_End;
  long  nV, nT, nT1, iFlag;
  double Time_nT, al_0, min_Dist_Diff;

case 2:
// apply car following logic

  outfile = fopen("carfolla.out", "a+");

  nV     = peUser->LTRIB[1];
  al_0   = XX[2];
  Dist_Appl = XX[5] - 35.;
  Dist_Appr = XX[5];
  Dist_Half = Dist_Appr + XX[6] / 2.;
  Dist_Totl = Dist_Appr + XX[6];
  Dist_Crit[nV] = Dist_Appr - Dist_Stop[nV][0];

case 3:
// apply dynamic dilemma zone

  if (peUser->LTRIB[1] == nTarget)
  {
    nV = nTarget;
    nT = 0;
    min_Dist_Diff = 9999.;
    Time_Min_Diff = 0.;

    while (nT <= (Time_Rete[nV][2]/dT))
    {
      Dist_Stop[nV][nT] = peUser->ATRIB[5] * Speed_Veh[nV][nT] +
                 pow(Speed_Veh[nV][nT], 2) / (2. * XX[4]);
      Dist_Remg[nV][nT] = Dist_Appr - Posit_Veh[nV][nT];
```


Validation

- Comparing simulated speed profiles with field data
  - Simulation Runs
    - Hartford: 5 vehicles in a platoon, McLean: 3 vehicles
    - 15 replications with different random seeds
    - Average speed in each zone
  - *t*-test
    - Statistical significance of the difference in average speed
    - H_0: $\mu = \mu_0$
    - $t\ (n-1)$ statistic

$$t = \frac{\bar{X} - \mu_0}{s/\sqrt{n}}$$

Validation

- Lead veh. speed profile: no significant difference

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	15.38
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
$t_{0.025}(14)$	2.1448	2.1448	2.1448

Validation

- Test speed profiles in a platoon
  - No Significant Difference
    - 1st, 2nd, 3rd, 4th, and 5th vehicles for Hartford
    - 1st, 2nd, and 3rd for McLean
- Simulation Model is Valid
  - Represent the speed profiles of vehicles in the dynamic dilemma zone methodology including car-following logic

Optimal Gate Operation Times

- Findings for the optimal gate operation times
  - Using all data groups in the valid simulation model
- 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

- 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

5 Conclusions and Recommendations

- Review of Objectives
  - Dynamic Dilemma Zone and Car-Following
  - Optimal Gate Delay and Gate Interval Time
  - Statistical Distribution of Driver Behavior
- Summary and Conclusions
  - Statistical Distribution of Driver Behavior
    - Definite tendency of speed reduction
    - Average speed of platoon is less than that of single vehicle
  - DDZ and Car-Following Model
    - DDZ exists in both cases of constant speed and speed reduction including car-following logic

Conclusions and Recommendations

- Summary and Conclusions (cont'd)
  - Simulation Model for Optimal Gate Operation Times
    - Gate delay and gate interval time based on minimizing DDZ
  - Validation
    - The proposed DDZ and Car-Following model is valid by comparing speed profiles with field data
  - Optimal Gate Operation Times are Obtained
    - Using all data groups for both sites: Hartford and McLean

Conclusions and Recommendations

- Recommendations
  - More data collection for interaction between veh. & train
  - Test and refine model for multi-lane HRIs
- Applications
  - Evaluating intergreen interval, yellow and all-red at HHI
  - Intelligent Transportation Systems (ITS)
    - Real-time traffic control at HHI, HRI, work-zone, incident area, merging area, lane closure, toll collection area, etc.
    - Advanced Traffic Management System (ATMS)
    - Automated Highway System (AHS)