USF Seminar

Developing Advanced Traffic Signal Control Algorithms: The Role of Connected Vehicles

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Tampa, FL
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FHWA EAR Project -- Advanced Signal Control Strategies based on Connected Vehicle Data

PATH/UC Berkeley, UC Riverside, BMW

Objectives/Scope:

- **Estimating of performance measures from CV data**
  - Determine penetration rates and sampling protocols
  - Data fusion with loop detector data

- **Traffic signal control for mobility**
  - Queue spill-back avoidance
  - Perimeter control in grid networks to prevent gridlock
  - Dynamic lane grouping

- **Traffic signal control for safety**
  - Dynamic all-red extension
  - Minimizing arrival rate on yellow change interval

- **ECO signal operations**
  - In-vehicle driver speed advisory for minimum fuel consumption
  - Integration of adaptive signal priority with driver advisory
Background: Traffic Flow Variability vs. Control

- Fixed-Time Plans
- Time of Day (TOD)
- No Detection
- May be actuated

- Fixed time plans
- Traffic responsive plan selection
- System detection

- Traffic responsive control
- On-line timing development
- Approach & system detection

- Adaptive control
- Measure & predict arrivals per cycle
- Extensive detection
Estimation of MOEs: Overview

Algorithms for estimating traffic conditions in arterials based on CV data

- Intersection level
  - Queue length

- Arterial level
  - Average speed, delay, # of stops, acceleration noise

Analyze the algorithms’ accuracy

Determine minimum penetration rate requirements
Test Sites

NGSIM Data: Peachtree St., Atlanta, GA
- 4 signalized intersections
- Vehicle ID, time, position, lane, speed, acceleration
- Resolution=0.1 sec
- Undersaturated traffic conditions

Simulated Data: El Camino Real, SF Bay Area
- 5 intersections
- Same trajectory information, resolution
- Oversaturated traffic conditions

Argote J., E. Christofa, Y. Xuan, and A. Skabardonis
Step 1. Discretization of time-space
Step 2. Identification of deceleration/acceleration points
Step 3. Filter outliers:
consider average distance between sampled vehicles
Step 4. Filtered deceleration/acceleration points
Intersection MOE—Queue Length (5/6)

Methods:

- Maximum Likelihood (ML)
- Method of Moments (MM)
- Kinematic Wave Theory (KWT)
Estimation of Arterial MOEs (1)

Average Speed

Undersaturated conditions

Oversaturated conditions
## Summary

<table>
<thead>
<tr>
<th>MOE</th>
<th>Penetration Rate (undersaturated)</th>
<th>Penetration Rate (oversaturated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Speed (km/hr)</td>
<td>35%</td>
<td>5%</td>
</tr>
<tr>
<td>Average Total Delay (sec/m)</td>
<td>50%</td>
<td>10%</td>
</tr>
<tr>
<td>Average Number of Stops</td>
<td>50%</td>
<td>20%</td>
</tr>
<tr>
<td>Acceleration Noise (m/s²)</td>
<td>10%</td>
<td>1%</td>
</tr>
</tbody>
</table>

_Argote J., E. Christofa and A. Skabardonis, “Connected vehicle penetration rate for estimation of arterial measures of Effectiveness, Transportation Research part C (2015), 298-312_
Minimum CV Penetration rate

**Motivation:**
The minimum penetration rate requirements vary depending on the traffic conditions.

<table>
<thead>
<tr>
<th>MOE</th>
<th>Min p (undersaturated)</th>
<th>Min p (oversaturated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Speed (km/hr)</td>
<td>35%</td>
<td>5%</td>
</tr>
<tr>
<td>Average Total Delay (sec/m)</td>
<td>50%</td>
<td>10%</td>
</tr>
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<td>Average Number of Stops</td>
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</tr>
<tr>
<td>Acceleration Noise (m/s²)</td>
<td>10%</td>
<td>1%</td>
</tr>
</tbody>
</table>

**Theoretical derivation:**

\[
S \geq \left( \Phi^{-1}(1 - \alpha)\sigma v \right)^2 \frac{0.1\bar{v}}{0.1\bar{v}}
\]

\[
S = \min \left\{ qpT, \left( \frac{G}{C} s \right) pT \right\} \Rightarrow \begin{cases} p \geq \frac{S_{\text{min}}}{qT} & \text{undersaturated arterial} \\ p \geq \frac{S_{\text{min}}}{\left( \frac{G}{C} s \right) T} & \text{oversaturated arterial} \end{cases}
\]

**Simulation test:**
Model of San Pablo Avenue (4-link segment)
Testing multiple scenarios: G/C = {0.20, 0.30, 0.35, 0.40, 0.50, 0.60}
q/s = {0.35, 0.40, 0.50, 0.60}
Signal Control Strategies for Mobility

- Infrastructure Control Based on Probe Data
  - Queue spill-back detection and control at an individual intersection approach
  - Control of congested urban grid networks
  - Adaptive priority for individual vehicles *(discussed in eco signal operations)*
  - Dynamic lane grouping

Queue Spillback Detection & Control

Queue Length Threshold, $L_{\text{lim}}$ (for the critical link)

- Early in the research: $L_{\text{lim}} = (1 - k)L$ (e.g. $k = 0.9$)
  - Issues: Independent of traffic conditions, creates oscillations in the activation/deactivation of the alternative spillback control strategy.

- Currently: $L_{\text{lim}} = L - \max\left\{F, \left(\frac{q^{u} C}{p} - \sum_{i=1}^{I_{\text{ca}}} S_{i}^{d} G_{i}^{d}\right) / NK_{j}\right\}$
  - Based on input-output analysis, to guarantee that a spillback cannot occur within the next cycle (dependent on traffic conditions).
  - Avoids oscillation issues in the activation of the alternative strategy.
Queue Spillback Detection & Control

Potential Spillback Detection (Methods):

- Gap length method, $X^*(p)$
  - Only requires Connected Vehicle information and the signal cycle time.
  - Based on the assumption that the number of cars until behind the last CV vehicle in the queue follow a geometric distribution with probability $1-p$, where $p$ is the market penetration rate.

$$\Pr(X \leq x | L_{\text{lim}}, p) = 1 - (1 - p)^{(NK_j,x)} \geq 1 - \alpha$$

$$X^*(p) = \min \left\{ L_{\text{lim}}, \frac{1}{NK_j} \left[ \frac{\ln(\alpha)}{\ln(1 - p)} \right] \right\} = \min \{ L_{\text{lim}}, X(p) \}$$
Potential Spillback Detection (Methods):

- Gap length method, $X^*(p)$ ($\alpha = 0.05$)

The method needs to be adapted when $p$ is low (or $X^* > L_{th}$), it is necessary to account for the cycles since the last CV was observed.
Queue Spillback Detection & Control

Potential Spillback Detection (Methods):

• Gap length method, $X^*(p)$, adapted for low penetration rates

$$X^*(n, p) = \text{mid}\left\{0, X(p) - (n - 1) \frac{\sum_{i=1}^{r_{cd}} s_i^d G_i^d}{NK_j}, L_{\text{lim}}\right\}$$

Cycles since last CV detection

- $n = 1$

- $n = 2$

- $n \geq 3$

Threshold location if $p = 1$

Threshold location for $\{p, n\}$
Potential Spillback Detection (Methods):

- Method based on kinematic wave theory
  - Requires CV info and signal settings (G/R, Cycle, Offset).
  - Method: use the last CV stopping point observed to project the queue length based on flow measurements, and compare that with $L_{lim}$.
Queue Spillback Detection & Control

Control concept

- Reduce green time for main arterial at upstream intersection
- Reduction should be such to allow only as many vehicles as the ones that get served by the downstream intersection within the cycle

Queue Spillback Detection & Control

<table>
<thead>
<tr>
<th>Equipped Car</th>
<th>Non-equipped Car</th>
</tr>
</thead>
<tbody>
<tr>
<td>X*</td>
<td>Queue Length Threshold ($L_{th}$)</td>
</tr>
</tbody>
</table>

[Diagram showing traffic flow and queue spillback control]
Queue Spillback Detection & Control

Test Site and Simulation Approach

- Three intersection segment of San Pablo Ave, Berkeley, was used to test the detection and alternative control strategy (the critical intersection being San Pablo and University with G/C = 0.35).
- Emulation-in-the-loop-simulation tests performed in AIMSUN.
- 20 tests were ran for each penetration rate level (0.05, 0.1, 0.15, 0.2, 0.25, 0.5, and 0.75).
- Each run includes a 10 min warm up period and 1 hour simulation with a variable demand profile (charging until oversaturation and discharging of the arterial).
# Queue Spillback Detection & Control

## Spillback Control Results:

<table>
<thead>
<tr>
<th>p</th>
<th>Average Delay (s/veh)</th>
<th>Maximum Queue Length (veh)</th>
<th>Average number of stops</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>40.12</td>
<td>14.42</td>
<td>1.00</td>
</tr>
<tr>
<td>10%</td>
<td>37.83</td>
<td>13.80</td>
<td>0.92</td>
</tr>
<tr>
<td>20%</td>
<td>38.16</td>
<td>14.23</td>
<td>0.92</td>
</tr>
<tr>
<td>50%</td>
<td>36.90</td>
<td>14.07</td>
<td>0.88</td>
</tr>
<tr>
<td>75%</td>
<td>34.99</td>
<td>13.09</td>
<td>0.83</td>
</tr>
</tbody>
</table>

## Results at the critical link

<table>
<thead>
<tr>
<th>p</th>
<th>Travel time (s/veh)</th>
<th>Average number of stops</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>112.95</td>
<td>1.64</td>
</tr>
<tr>
<td>10%</td>
<td>114.08</td>
<td>1.61</td>
</tr>
<tr>
<td>20%</td>
<td>115.70</td>
<td>1.64</td>
</tr>
<tr>
<td>50%</td>
<td>115.76</td>
<td>1.63</td>
</tr>
<tr>
<td>75%</td>
<td>112.43</td>
<td>1.54</td>
</tr>
</tbody>
</table>
Congested Grid Networks
Post Oak Network, Houston TX

Intense commercial and entertainment activities, major attraction in Houston Metropolitan Area.
One of the most congested areas in Houston (average speeds of 7.6 mph–free flow speed 50 mph)
The period analyzed is the PM peak period
Arrows shown represent the extension of queue spillback detected in the model.

<table>
<thead>
<tr>
<th>MOEs</th>
<th>Units</th>
<th>Original</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Delay Time</td>
<td>hr</td>
<td>2079.6</td>
</tr>
<tr>
<td>Average Density</td>
<td>veh/km</td>
<td>58.8</td>
</tr>
<tr>
<td>Average Speed</td>
<td>km/hr</td>
<td>7.6</td>
</tr>
<tr>
<td>Stop Time</td>
<td>hr</td>
<td>1944.7</td>
</tr>
<tr>
<td>Total Distance Travelled</td>
<td>km</td>
<td>20184.9</td>
</tr>
<tr>
<td>Total Travel Time</td>
<td>hr</td>
<td>2493.2</td>
</tr>
<tr>
<td>Vehicles Out</td>
<td>vehs</td>
<td>19120.8</td>
</tr>
<tr>
<td>Vehicles Waiting Out</td>
<td>vehs</td>
<td>4758.6</td>
</tr>
<tr>
<td>Time of spillback detection</td>
<td>%</td>
<td>81%</td>
</tr>
</tbody>
</table>
Post-Oak Existing Conditions

- Fixed time signal control
- 150 second cycle

Arrows show the formation of the first spillbacks are showed in the network. These are defined as critical spillbacks

A threshold of 80% was determined. If a CV was detected in this area with a velocity lower than 5 km/hr, spillback was considered detected.

Once spillback is detected, the following mitigation control strategies are activated:

- **Perimeter control**: reduce the green times in the entrances of the network

- **Phase service change**: downstream intersection turns directly to green (to allow the through movement). The upstream intersection, the phase changes directly to red
Perimeter Control Strategy

- Reduced green times by 10% when spillback is detected
- Unattended internal inputs
## Results of Perimeter Control

- Once a spillback is detected, green time on main entrances to the network are reduced by 10%.
- Effectiveness of strategy is affected by the internal flows in the network (peak PM period).

<table>
<thead>
<tr>
<th>MOEs</th>
<th>Units</th>
<th>Current strategy</th>
<th>Current strategy + spillback detection</th>
<th>% benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Delay Time</td>
<td>hr</td>
<td>2079.6</td>
<td>2089.0</td>
<td>-0.5%</td>
</tr>
<tr>
<td>Average Density</td>
<td>veh/km</td>
<td>58.8</td>
<td>55.2</td>
<td>6.2%</td>
</tr>
<tr>
<td>Average Speed</td>
<td>km/hr</td>
<td>7.6</td>
<td>7.8</td>
<td>2.9%</td>
</tr>
<tr>
<td>Stop Time</td>
<td>hr</td>
<td>1944.7</td>
<td>1951.9</td>
<td>-0.4%</td>
</tr>
<tr>
<td>Total Distance Travelled</td>
<td>km</td>
<td>20184.9</td>
<td>21050.5</td>
<td>4.1%</td>
</tr>
<tr>
<td>Total Travel Time</td>
<td>hr</td>
<td>2493.2</td>
<td>2513.5</td>
<td>0.8%</td>
</tr>
<tr>
<td>Vehicles Out</td>
<td>vehs</td>
<td>19120.8</td>
<td>19526.4</td>
<td>2.1%</td>
</tr>
<tr>
<td>Vehicles Waiting Out</td>
<td>vehs</td>
<td>4758.6</td>
<td>5077.2</td>
<td>-6.7%</td>
</tr>
<tr>
<td>Time of spillback detection</td>
<td>%</td>
<td>81%</td>
<td>85%</td>
<td>-4.7%</td>
</tr>
</tbody>
</table>
Arterial Analysis – Perimeter Control

Existing Intersection Delay (s/veh)
Intersection Delay with perimeter control (s/veh)
Benefit (%)

Improvements on intersection delay on arterial without internal flows
Alternative Strategy

- Provide extra green time (to improve capacity) at the approaches with critical spillbacks.
- Reduce the system cycle time to 120 seconds.
The proposed strategy allows a higher flow than the current strategy.
### Results (20% penetration rate)

<table>
<thead>
<tr>
<th>MOEs</th>
<th>Units</th>
<th>Current strategy</th>
<th>Current strategy + spillback detection</th>
<th>% benefit</th>
<th>Proposed strategy</th>
<th>Proposed strategy + spillback detection</th>
<th>% benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Delay Time</td>
<td>hr</td>
<td>2079.6</td>
<td>2072.2</td>
<td>0.4%</td>
<td>1920.9</td>
<td>1896.7</td>
<td>1.3%</td>
</tr>
<tr>
<td>Average Density</td>
<td>veh/km</td>
<td>58.8</td>
<td>54.5</td>
<td>7.4%</td>
<td>56.0</td>
<td>53.4</td>
<td>4.6%</td>
</tr>
<tr>
<td>Average Speed</td>
<td>km/hr</td>
<td>7.6</td>
<td>8.1</td>
<td>5.4%</td>
<td>8.8</td>
<td>8.8</td>
<td>0.3%</td>
</tr>
<tr>
<td>Stop Time</td>
<td>hr</td>
<td>1944.7</td>
<td>1926.6</td>
<td>0.9%</td>
<td>1774.9</td>
<td>1752.9</td>
<td>1.2%</td>
</tr>
<tr>
<td>Total Distance Travelled</td>
<td>km</td>
<td>20184.9</td>
<td>21624.3</td>
<td>6.7%</td>
<td>22468.1</td>
<td>22275.0</td>
<td>-0.9%</td>
</tr>
<tr>
<td>Total Travel Time</td>
<td>hr</td>
<td>2493.2</td>
<td>2533.6</td>
<td>1.6%</td>
<td>2441.2</td>
<td>2407.8</td>
<td>-1.4%</td>
</tr>
<tr>
<td>Vehicles Out</td>
<td>vehs</td>
<td>19120.8</td>
<td>19970.6</td>
<td>4.3%</td>
<td>20519.2</td>
<td>20607.6</td>
<td>0.4%</td>
</tr>
<tr>
<td>Vehicles Waiting Out</td>
<td>vehs</td>
<td>4758.6</td>
<td>4669.0</td>
<td>1.9%</td>
<td>3808.2</td>
<td>3563.0</td>
<td>6.4%</td>
</tr>
<tr>
<td>Time of spillback detection</td>
<td>%</td>
<td>81%</td>
<td>79%</td>
<td>1.6%</td>
<td>85%</td>
<td>75%</td>
<td>9.7%</td>
</tr>
</tbody>
</table>

#### Total delay on network (hr)

Without spillback detection: 2079.6
With spillback detection: 2072.2

#### Number of trips ended

Without spillback detection: 19120.8
With spillback detection: 19970.6
Impacts on an Arterial — Alternative Strategy

Existing Intersection Delay (s/veh)
Intersection Delay with proposed strategy (s/veh)
Benefit (%)
Most signal control strategies assume fixed lane utilization on intersection approaches.

Spatial variations in traffic demand degrade intersection performance.

Solutions for predictive situations (TOD lane assignments)
Dynamic Lane Allocation/Grouping (DLG) (1)

- Changing lane allocation in response to real-time movement demands
- Allows exclusive and shared lanes

Requirements
- O-D information (Connected vehicles)

Assumed demand is known and can be predicted
Given real-time O-D demands at a signalized intersection, how to dynamically determine the lane assignment to improve performance?

**Approach:**
- For each intersection leg find the optimum lane grouping
  - Minimize the max lane flow ratio $y$
  - $(y = \text{flow/saturation flow})$
  - St: Allowable movements (safety constraints)

**Sub-problem:**

*Determine the steady state traffic flow among lanes within each lane group also*
Evaluation of DLG

Numerical Analysis

- Scenarios:
  - Keep total demand fixed
  - Increase total demand (oversaturated conditions)
    - Demand ratio among movements
    - # Lanes per approach
    - Fixed timing vs. “adaptive” timing (EQUISAT or HCM2000 QEM)
  - MOEs \( \text{max lane flow ratio, average delay sec/veh (per HCM)} \)

Simulation

- PARAMICS microsimulation model
- MOEs: Delay, Stops, Fuel, Emissions

Results: Max Lane Flow Ratio/Lane (1)

Under DLG, max lane flow ratio always keeps as low as 0.2
Higher DLG benefit in terms of max lane flow ratio when demand deviation increases
Performance Analysis: Average Delay

Under DLG scenario, average delay remains almost constant
Discussion

Findings:
- Dynamic lane allocation appears promising to address spatial demand variation
- Improves efficiency and robustness
- Higher benefits for multilane approaches

Challenges:
- Need O-D demands
- Existing and emerging technologies
- Safety issues and potential capacity reduction:
  - Induced lane changes
  - Lane transition in and out
  - Driver expectancy warning

Opportunities:
- Integration with adaptive signal control strategies
Appendix I: Minimize max flow ratio

Minimizing maximum flow ratio for each arm

Problem:
Given demand matrix \( Q(n) \), to find the optimum lane grouping \( \delta = (\delta_{i,j,k}) \) by the objective function

\[
\min \max y_i(n),
\]

subject to movement constraints.

Sub-problem: estimate steady state traffic flow by
Given \( \delta = (\delta_{i,j,k}) \), \( \min (\max_k y_{i,k}) \) \n
such that \( y_{i,k_1} = y_{i,k_2} \), for any \( 1 \leq k_1, k_2 \leq N_i^A \) that satisfies following conditions

\[
\delta(i, j, k_1) = \delta(i, j, k_2) \quad \forall j \text{ and } \sum_j \delta(i, j, k_1) = \sum_j \delta(i, j, k_2) = 1
\]

(i.e., lane \( k_1 \) and lane \( k_2 \) are both exclusive lanes for the same movement)

and \( y_{i,k_1} \geq \min_{k_2} y_{i,k_2} \), \n
\[
\forall k_1, k_2 \text{ that satisfies } \sum_j \delta(i, j, k_1) > 1, \sum_j \delta(i, j, k_2) = 1
\]

and \( \forall j, \delta(i, j, k_2) \leq \delta(i, j, k_1) \);

(i.e., lane \( k_1 \) is a shared lane and lane \( k_2 \) is any exclusive lane with common movement along lane \( k_1 \))

\[
\sum_j f(i, j, k) = 1, \quad \text{for any } k = 1, \ldots, N_i^A
\]

\[
0 \leq f(i, j, k) \leq \delta(i, j, k), \quad \text{for any } k = 1, \ldots, N_i^A, j = 1, \ldots, N_T.
\]
Eco-Driving

Messages
“Here I am”
Signal Phase & Timing (SPaT)

Application: Dynamic Speed Advisory (source: UC & BMW)

14% Reduction in Fuel Use
Communication System

- wired/wireless backhaul
- Cloud server (Amazon Web Services)
- 4G/LTE network (Verizon Wireless)
- modified J2735 messages
- El Camino / Richmond Field Station test fields
- BMW research vehicle running speed advisory system
BMW Research Vehicle
Test Field Setup

→ due to GPS positioning problems, the yellow leg is unusable

→ data gathering for blue leg only

Length of test section: 320 m (1050 ft)

Speed limit: 25 mph

Default Signal Timing: 60 sec cycle
  (30 sec green; 3 sec yellow; 27 sec red)

All data is gathered from the vehicles CAN buses, e.g. consumption from digital motor management.

4G/LTE communication link, 1Hz update frequency.
Scenarios

1. Uninformed Driver (Baseline Scenario)
   - drive without speed recommendation
   - driver behaves economic reasonable

2. Informed Driver
   - follow speed-recommendation

3. APIV (Adaptive Priority for Individual Vehicle) & Uninformed Driver
   - drive without any speed recommendation
   - intersection adapts timing with individual vehicle priority

4. APIV & Informed Driver
   - drive with speed-recommendation
   - intersection adapts timing with individual vehicle priority

n=270
n=292
n=108
n=108
RFS Testing: Test Results (3)

- Driving without slowing down in green phase
- Slowing down or even stop in red phase

Graph showing fuel consumption [l/100km] with different categories:
- Uninformed
- Informed
- API Uninformed
- API Informed
RFS Testing: Test Results (3)

Bar chart showing:
- Uninformed: 48.57%
- Informed: 30.60%
- APIV Uninformed: -36.99%
- APIV Informed: -69.50%

Legend:
- Stop Frequency (%)
- % of Change

Bar chart notes:
- Stop Frequency (Uninformed) vs Informed
- APIV Change (Uninformed) vs Informed

Values:
- Stop Frequency Uninformed: 48.57
- Stop Frequency Informed: 30.60
- APIV Uninformed: -36.99
- APIV Informed: -69.50
RFS Testing: Test Results (4)
Field Test: El Camino Real
El Camino Real Setup

- **Electric Control Cabinet 1**
  - Modem 1
  - Embedded PC 1
  - 3G antenna
  - Shadow controller
  - Ethernet
  - RS-232
  - Traffic Signal (intersection 1)

- **Electric Control Cabinet 2**
  - Modem 2
  - Embedded PC 2
  - 3G antenna
  - Shadow controller
  - Ethernet
  - RS-232
  - Traffic Signal (intersection 2)

- **Electric Control Cabinet 3**
  - Modem 3
  - Embedded PC 3
  - 3G antenna
  - Shadow controller
  - Ethernet
  - RS-232
  - Traffic Signal (intersection 3)

- **Server**
  - Internet
Algorithm Overview (1)

1. Select best arrival time or decide to stop at intersection

2. Calculate speed trajectory

3. Get speed recommendation from trajectory
Algorithm Overview (2)

1. guaranteed green of any cycle reachable?
   - yes: select best arrival time
   - no: “maybe-green” reachable

2. calculate trajectory
   - no: calculate stop trajectory

3. get speed from trajectory
   - recommended speed
   - no recommendation
Challenges

Speed recommendation changes at intersection
Looking Ahead

- Automation
- Connected Veh
- ATM

Diagram:
- Capacity
- Current technologies
- Safety
- Air quality
Background: Initial Deployment Plans

Planned US VII Deployment ’06