Optimization of Work Zone Decisions

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Outline

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- **Problem Statement**
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- **Methodology**
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- **Future Work**

1. Motivation

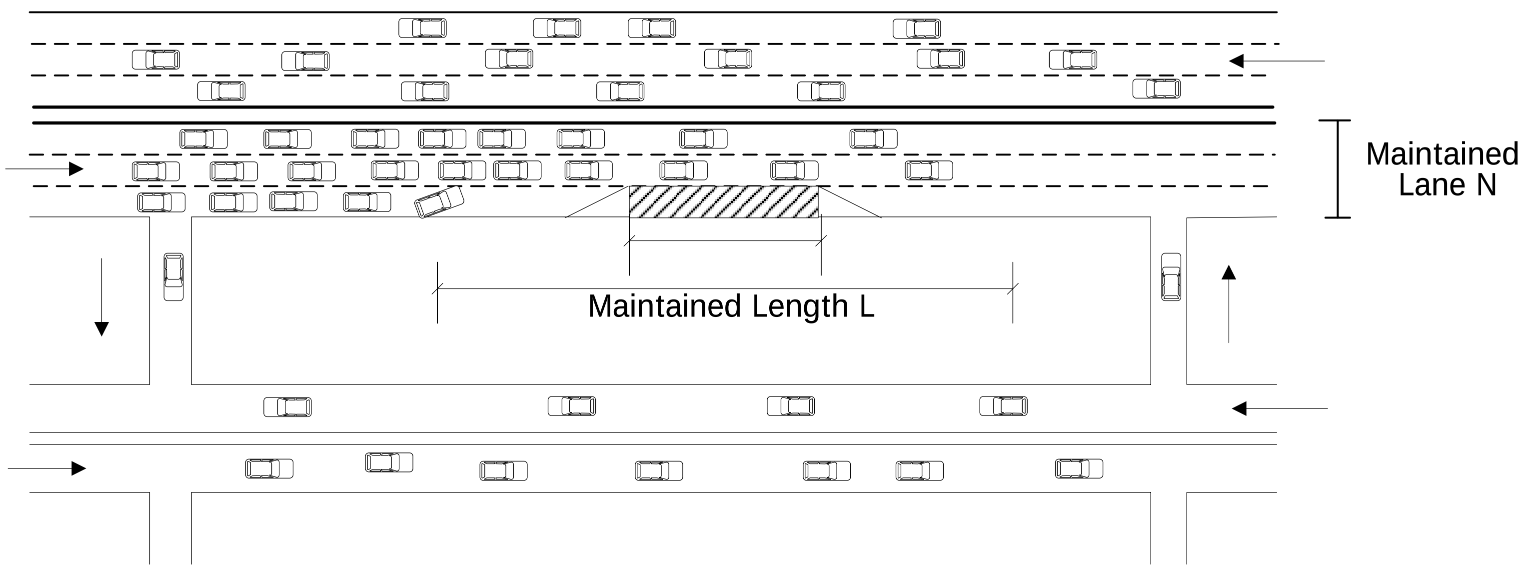
- The number, duration, and scope of maintenance projects are increasing to provide satisfactory level of service.

- Highway maintenance requires lane closures, which can greatly affect traffic mobility and safety.

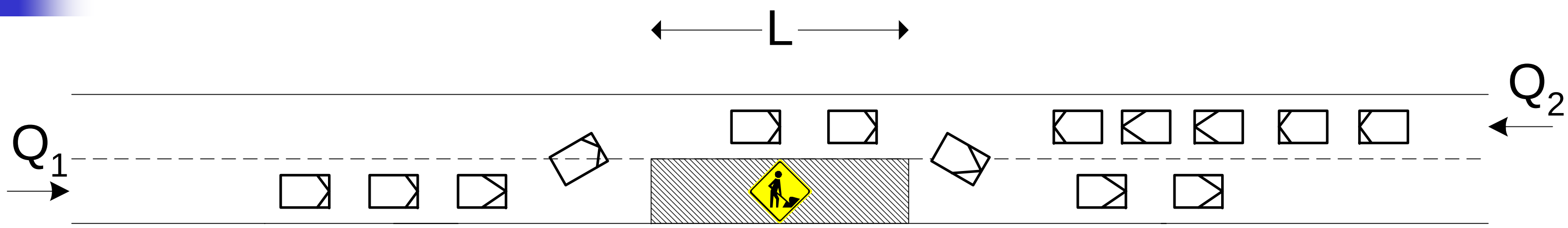
- A current trend encourages construction engineers, traffic engineers, and other technical specialists to work together in developing comprehensive work zone management plans. Some major decisions which should be jointly analyzed include:
  - How should a road section be divided into work zones? How long and wide should the work zones be?
  - At what times should the lanes in each work zone be closed and reopened to traffic under time-varying traffic inflows?
  - What traffic impact mitigation strategies (e.g., detours, work acceleration) should be used?
  - Which intensity level (e.g. overlay thickness) should be chosen for economic durability?

2. Problem Statement

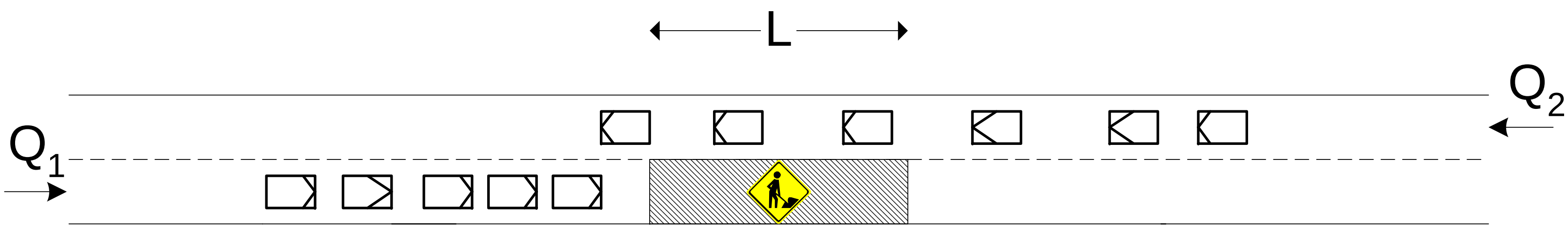
- Given a project to maintain a highway section with length L and number of lanes N, find the best combination of work zone decisions to complete the maintenance work.



Simple Work Zone on Two-Lane Road



(a) Direction 1 (from West to East)

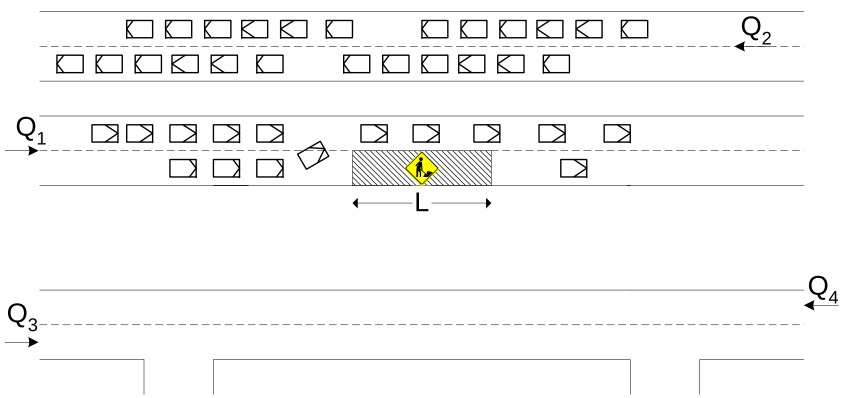


(b) Direction 2 (from East to West)

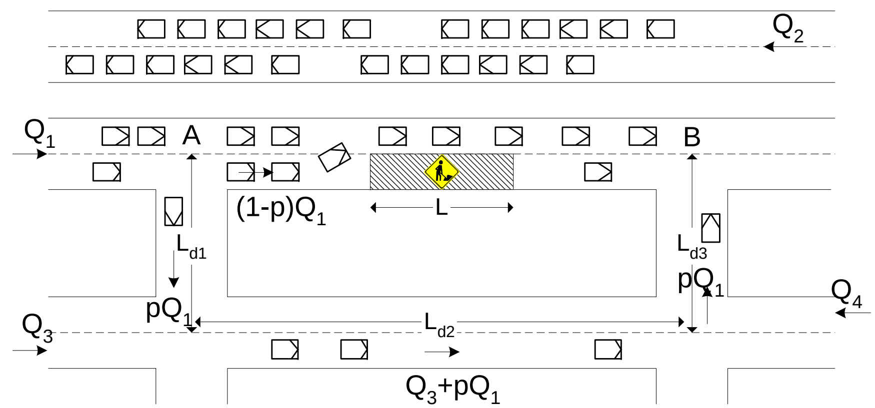
Vehicle Movements and Geometry of Work Zones for Two-Lane Highways

Source: Schonfeld and Chien (1999)

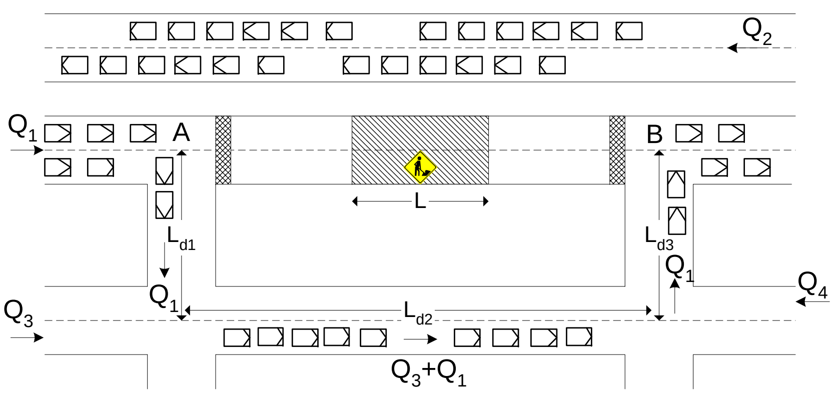
Work Zone Alternatives on 4-lane Road



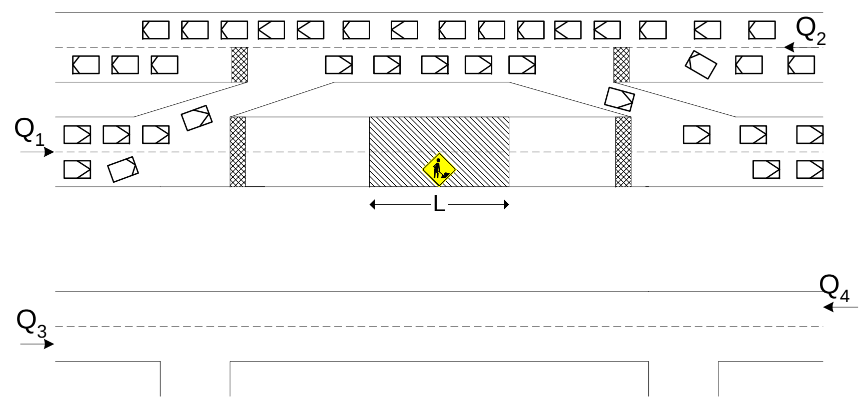
Partial Closure



Partial Closure with Detour



Full Closure with Detour



Crossover

Short-Term and Long-Term Work Zone Decisions

Decision Type	Decisions	Short-term Impacts	Long-term Impacts
Pavement Design	New Pavement Type	√	√
	Intensity Level	√	√
Lane Closure	Work Zone Configuration	√	
	Work Zone Scheduling	√	
Traffic Impact Mitigation Strategies	Work Zone Traffic Control	√	
	Detour	√	
	Accelerated Construction	√	(√)
	……	√	(√)

3. Literature Review

- **Short-term project-level work zone management optimization**
  - McCoy et. al.: simple optimization framework to optimize zone length
  - Schonfeld, Chien, Chen, Tien(1999-2008):
    - Multiple zone length, lane closure type, scheduling, and diversion fraction under steady and time-varying traffic flow in a simple network
    - Work time-cost tradeoff
    - pavement thickness (durability)
  - Adeli et. al.(2003): Neural network and SA
  - Chien, Tang (2008-2010): time-cost tradeoff, user-equilibrium assignment, GA
- **Long-term project-level maintenance decision optimization**
  - Determine the optimal intensity (e.g. overlay thickness) and frequency (timing) of the pavement maintenance and rehabilitation activities.
  - The problem is formulated as a optimal control problem and solved by DP, numerical optimization method, or heuristic algorithms.

Needed improvements:

- Jointly optimize short-term and long-term maintenance decisions.
- Consider non-uniform work zone configurations.
- Consider traffic impact mitigation strategies.
- Take advantage of cyclical demand variations in designing periodic lane closure schedules.
- Use simulation in addition to analytic traffic flow and queuing models, to improve network representation and precision of results.

References

- Peter Chen, “Integrated Management of Highway Maintenance and Traffic,” Dec. 2002.
- Ning Yang, “Optimization of Highway Work Zone Decisions Considering Short-Term and Long-Term Impacts,” May 2010.
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- Chien, S., Tang Y., and Schonfeld, P. “Optimizing Work Zones for Two - lane Highway Maintenance Projects,” *Journal of Transportation Engineering*, ASCE, 128-2, March/April 2002, pp.145-155.
- Chen, C.H. and Schonfeld, P. “Work Zone Lengths for a Four - lane Road with an Alternate Route,” *Journal of Transportation Engineering*, ASCE, 131-10, Oct. 2005, pp. 780-789.
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4. Methodology

4. 1. Short-Term Decision Optimization

All decisions have negligible/equal impacts on the pavement performance in future years.

- Basic Assumptions
- Decision Variables
- Objective Function
  - Min One-time Work Zone Cost = Agency Cost + User Cost

    Model 1-1: for General Work Zones

    Model 1-2: for Periodic Work Zones

    Model 1-3: for Single Work Zone with steady traffic flow
- Optimization Algorithm

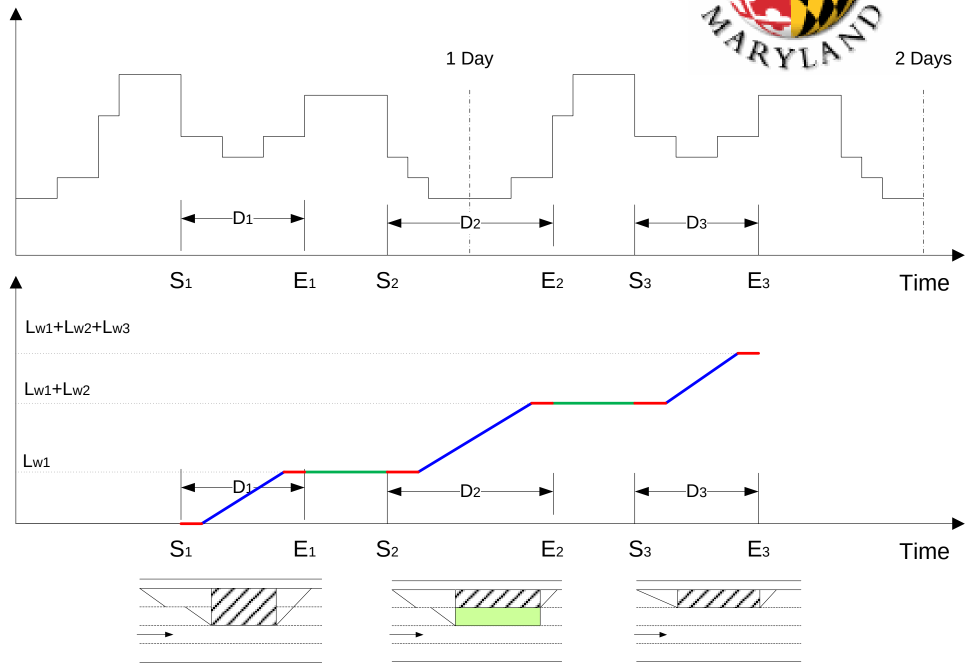
Basic Assumptions

- Project-Level analysis in planning stage
- Road network consisting of a mainline corridor and a detour route
- One work zone at a time
- Traffic analysis:
  - Time-varying traffic volume
  - Two user classes (autos and trucks)
  - Three models to determine time-varying detour fraction
    - System Optimum (SO)
    - Logit-based Route Choice Model (RC)
    - User Equilibrium (UE)

Short-term Decisions

- Work zone scheduling

  Start Time: S_i
  End Time: E_i



- Work zone configuration

  Number of Zones: m
  Zone Dimension:
  $L_i,\ N_i\ (=N_{wi} + N_{ai}),\ N_{ci}$

- Combination of traffic mitigation strategies

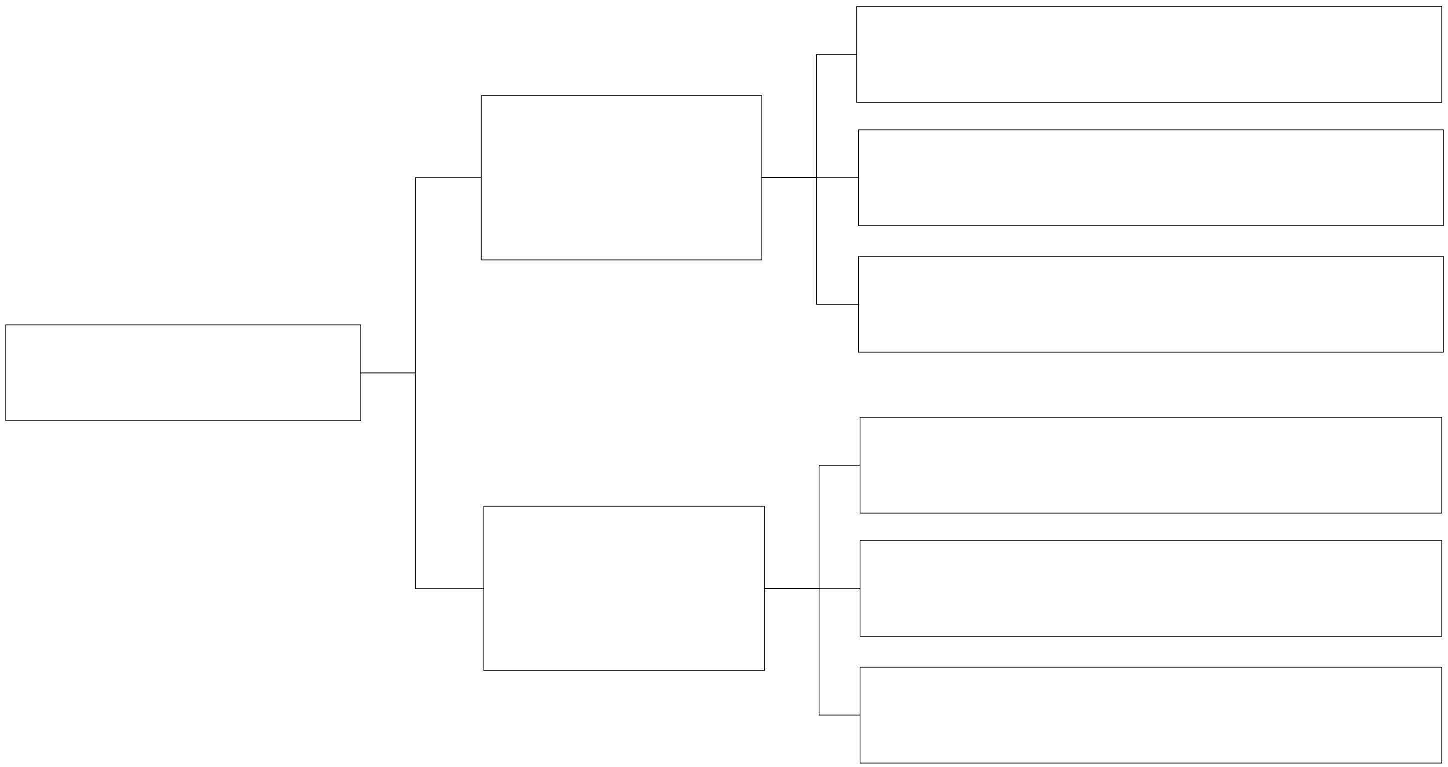
Fixed employment cost per zone	$\beta 1$
Additional cost required per unit time	$\beta 2$
Adjustment of the work zone capacity	δw
Adjustment of the detour capacity	δd
Adjustment of traffic diversion percentage	δp
Detour Model	*SO/UE/RC*

Adjustment of unit maintenance cost	$\delta z2$
Adjustment of unit maintenance time	$\delta z4$

ID of the selected option: $k_{Y,i} \in \{1, 2, \ldots, K_Y\}$
where,
Y = # of strategy types
K_Y = # of options of the strategy type Y

Measure of Cost-Effectiveness

- One-Time Work Zone Total Cost



Cost Components

- Short-term Agency Cost ($C_{A,i}$)
  - Maintenance Cost (per zone)

    = fixed cost + length/width dependent cost

    $$C_{M,i} = z_1 + z_2 \cdot (1 + f_2) \cdot N_{wi} \cdot L_{wi}$$

  - Traffic Mitigation Cost (per zone)

    = fixed cost + length/width dependent cost

    $$C_{S,i} = \sum_{k=1}^{K} b_{k,i} (\beta_{1k,i} + \beta_{2k,i} D_i)$$

  - Equipment/Labor Idling Cost

    = idling time * idling cost per time unit

    $$C_{I,i} = (S_{i+1} - E_i) v_i$$

- Short-term User Cost ($C_{U,i}$)
  - Travel Delay Cost

    Reduced Capacity

    Reduced Speed

    Detour
  - Vehicle Operating Cost

    Speed-Change VOC

    Queue Idling VOC

    Detour VOC
  - Expected Accident Cost

    = expected crash rate * avg. cost per crash

Travel Delay Estimation

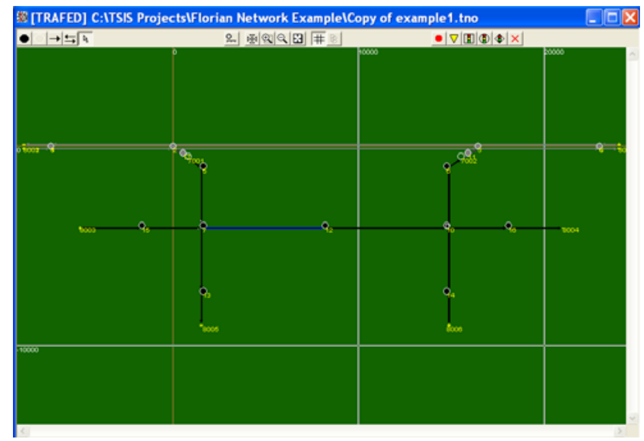
- Travel Delay Estimation Methods
  - Simulation Method

    Obtain suitable MOE

    Network-wide Average Statistics

    • Costly in terms of data preparation and computational time

    • Restrictions in simulation models may bias the results

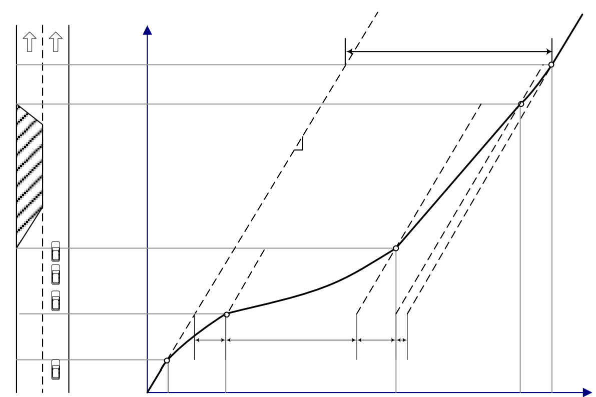


  - Analytical Method

    Construct mathematical models

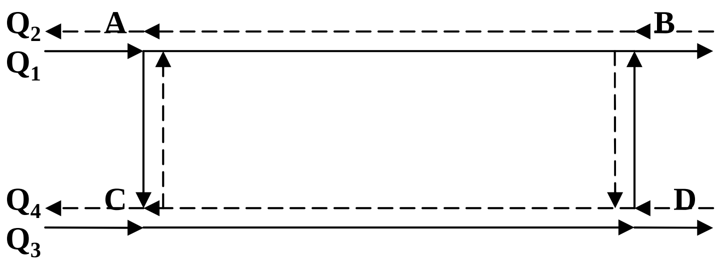
    Mainline Delay { Deceleration Delay, Acceleration Delay, Moving Delay, Queuing Delay, Randomness Delay }

    Detour Delay

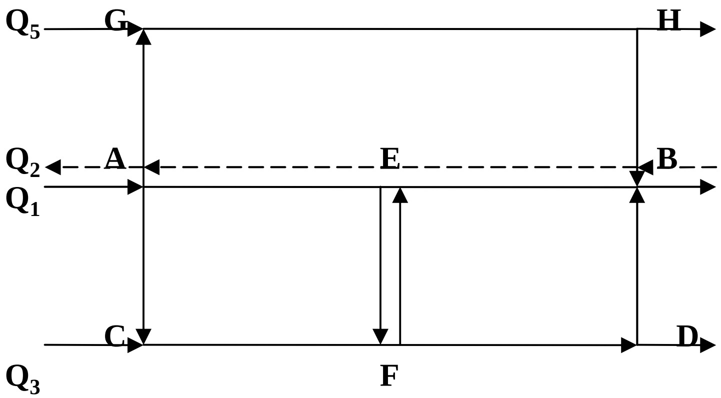


(1) Analytic Model

- **Scope of Analytic Model**
  - Steady Traffic Demand
    - Two-lane two-way highway
    - Multiple-lane two-way highway
    - Single detour
    - Simple Network



  - Time-Dependent Traffic Demand
    - Two-lane two-way highway
    - Multiple-lane two-way highway
    - Predefined multiple detours
    - Simplified Network



Analytic Model

- User Delay

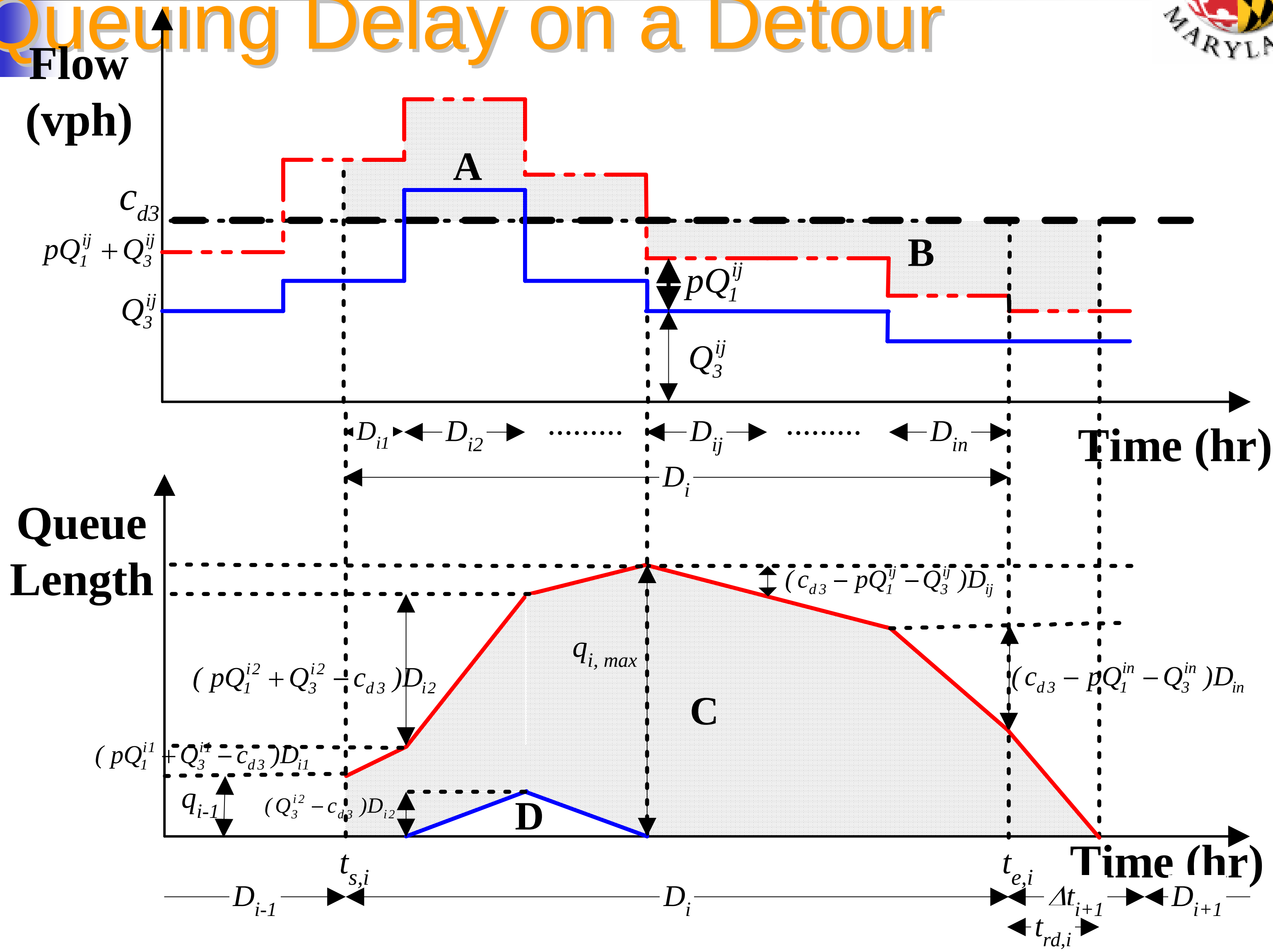
  = Queuing Delay + Moving Delay

Queuing Delay -- Deterministic queuing model

Speed Change -- Greenshields' Model

Sum of
- Traffic flow along mainline
- Diverted traffic flow along detour route
- Original traffic flow on detour route

Queuing Delay on a Detour



Queuing Delay and Dissipation of Queue Length

Simulation Model

- **Simulation Software - CORSIM**
  - Two-lane two-way surface street - actuated signal control
  - Multiple-lane two-way surface street - lane channelization
  - Multiple-lane two-way freeway - **lane-specified blockage incident**

- **Simulating Various Alternatives**
  - **One / Multiple Lane Closure**

    Add blockage incidents on specified lanes in the work zone link
  - **Crossover**

    Add blockage incidents on specified lanes in the work zone link
    Add blockage incidents on specified lanes in the counter work zone link
  - **Detour**

    Add blockage incidents on specified lanes in the work zone link
    Change turn movements information along the detour path

Simulation Model

- **Inputs users should provide** **- CORSIM Input File (*.trf)**
  - Physical network
  - Traffic information
  - Well-calibrated simulation model (calibrating parameters such as driver the response lag time and car following sensitivity factor)
- **Work zone information users should define**
  - Maintained Road Information (Work zone link, Mainline route, etc.)
  - Detour Information (Detour route, Diverted Fraction, etc.)
- **Simulation parameters users should specify**
  - Rubbernecking factor on the open lanes
  - Car following sensitivity factor along the work zone link
  - Free flow speed along the work zone link
  - Number of simulation replications

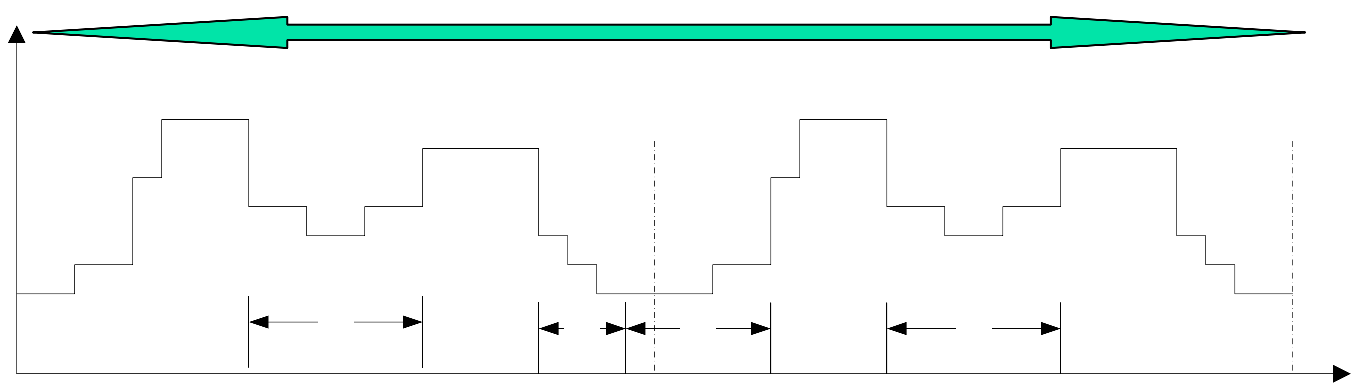
Work zone Capacity

Optimization Models

Model 1-1:

- General Objective Function
  - Minor/Regular Maintenance (lasts several hours or days)
  - *m* = total number of zones required to complete the project $m_{\max} = \left\lfloor \frac{D_T - L_T \cdot z_{4,\min}}{z_3} \right\rfloor$
  - Objective Function:

Min $F_1(m, \vec{V}) = C_T(m, \vec{V})$

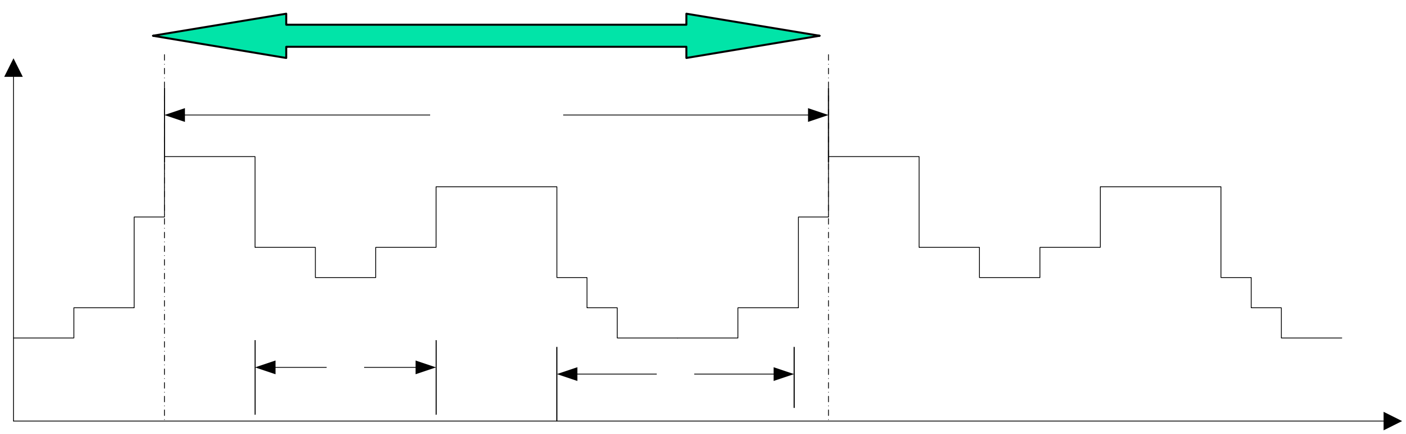


Model 1-2:

- Modified Objective Function for Periodic Work Zones
  - Major M&R (Lasts several days/weeks/months)
  - Recurrent lane closure in a cyclic period (day/week)
  - ***m'*** = number of zones in one cyclic period
  - Objective Function:

$$m'_{\max} = \frac{D'_T}{D_T} m_{\max}$$

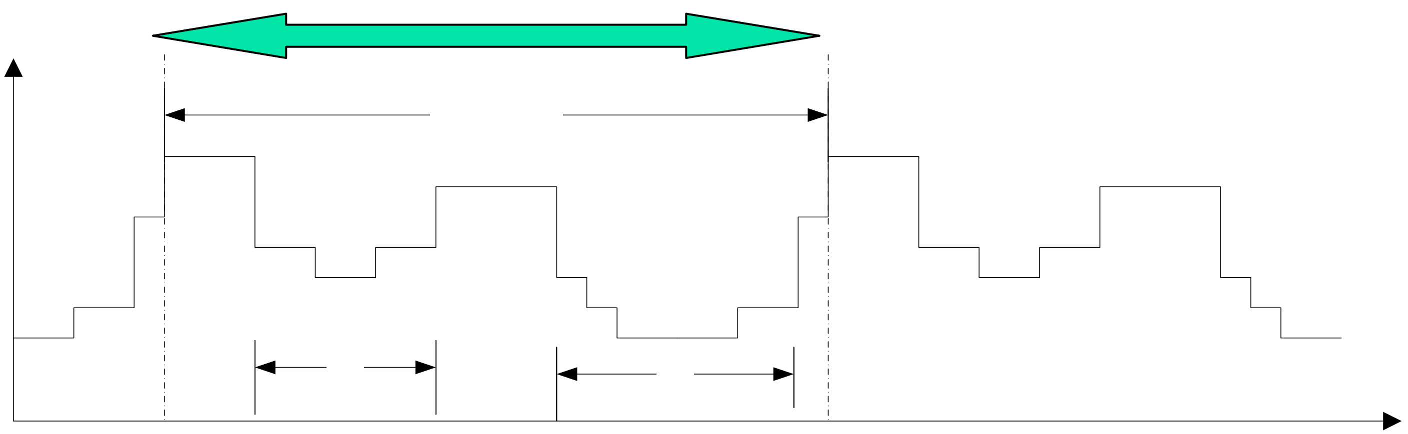
Min $$F_2(m', \vec{V}) = C'_T(m', \vec{V}) \frac{L_T}{L'_T}$$



Model 1-3:

- Simplified Objective Function for Single Work Zone
  - Steady Traffic Volume
  - Discrete decision variables (e.g. traffic management strategy) are given
  - No Idling Cost
  - Objective Function:

Min $$F_3(L) = \frac{C_T(L)}{L}$$



Constraints

- Project Requirements
  - Total maintenance lane-mile constraint
  - Maximum allowable project duration
- Zone scheduling constraint
  - Non-overlapping zone scheduling constraint
- Strategy implementation constraint
  - Only one option of a strategy can be selected
- Other optional constraints
  - Maximum allowable queue length
  - Uniform zone width constraint
  - Recurrent zone constraint
  - Mutually excusive strategy constraint

Optimization Procedure

- Objective function evaluated with analytical model
  - A complex closed-form formulation for the objective function
  - Combinatorial nature of the mathematical model
- Objective function evaluated with CORSIM simulation model
  - Lack a closed-form expression for the objective function
- Optimization problem solving method
  - Heuristic method
    - Two State Population-Based Simulated Annealing (2PBSA)
  - Objective function evaluation method
    - Analytical method
    - Simulation method
- Constraint handling
  - Repairing method
  - Penalty method

PBSA

- Meta-heuristic combining neighborhood search and global search
- Avoid getting trapped in a local extreme by sometimes moving in a locally worse direction

•Solution Representation

•Initial Solution Generation

•New Solution Generation

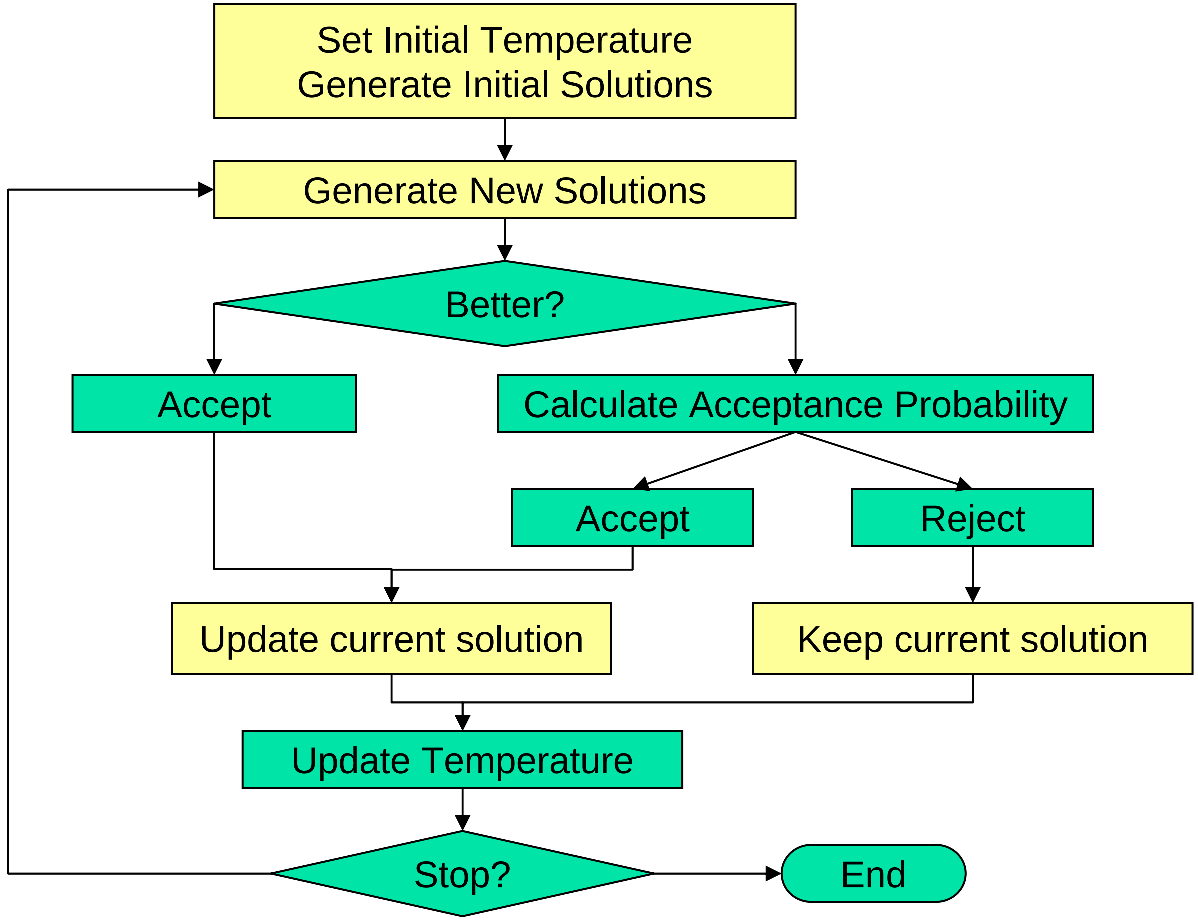
  •Mutation

  •Crossover

•Objective Function Evaluation

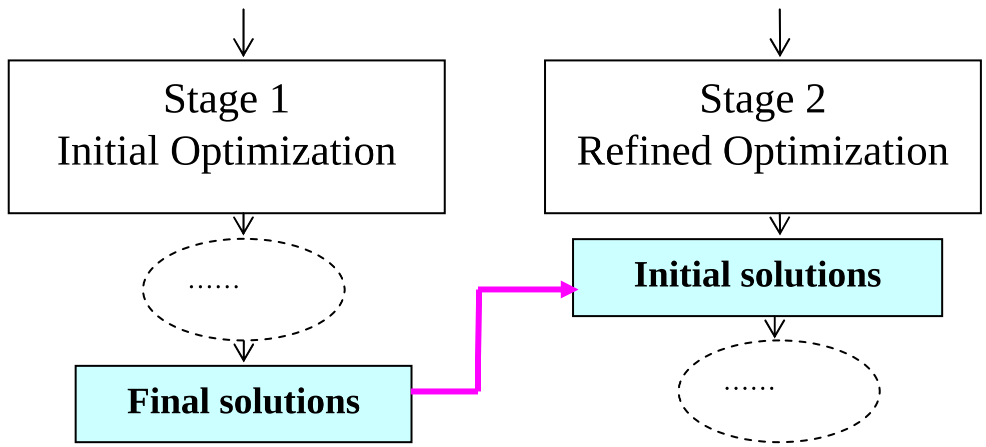
•Constraint Handling Method

•Stopping Criterion



2PBSA

- Two Stage Population-based Simulated Annealing Algorithm (2PBSA)

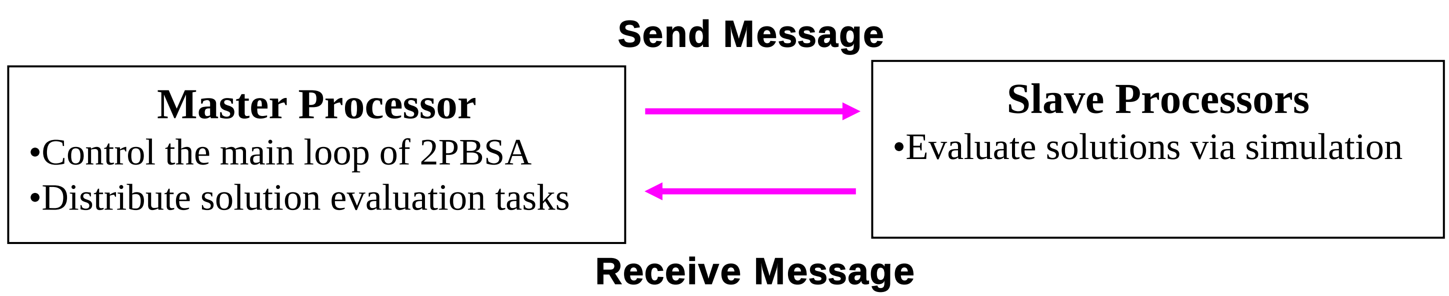


- **Phase 1-** Initial Optimization
- Population-based SA
- A Wide Search in large solution space
- Focus on searching for best work zone division and scheduling

- **Phase 2-** Refined Optimization
- Population-based SA
- A Refined Search inside relatively-good neighborhood provided by the first phase
- Focus on searching for best traffic mitigation strategies

2PBSA based on Simulation

- Simulation-based Optimization
  - Advantage: Traffic control performance, network traffic impact
  - Disadvantage: Time-consuming
- Speed-up Method
  - Hybrid Method
    - 2SA Phase 1: based on analytical model for a simplified network
    - 2SA Phase 2: based on simulation model
  - Parallel Computing
    - Distribute evaluation jobs to multiple processors
    - Parallelization model: Master-Slave parallelization paradigm



4. Methodology

Joint Optimization of Short-Term and Long-Term Decisions

- Basic Assumptions
- Decision Variables
- Objective Function
  - Max Cost-Effectiveness Index

$$CEI = \frac{EI}{CI} = \frac{\frac{1}{CL}\int_0^{CL} AADT(t)\cdot P(t)\cdot dt}{C_{CL}}$$

Avg. AADT*PSI

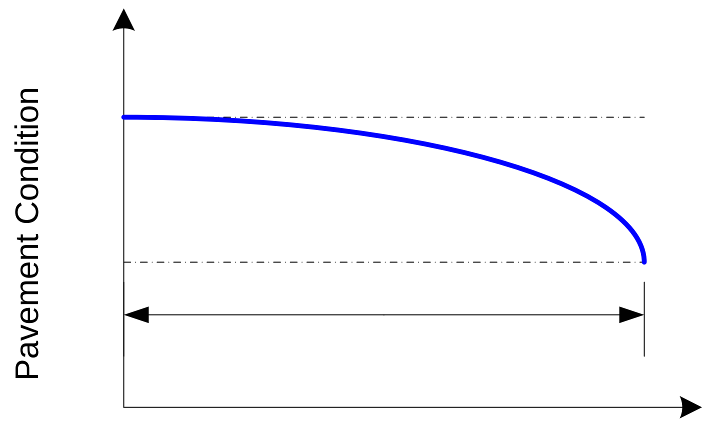
EUAC

- Constraints
- Optimization Framework

Basic Assumptions

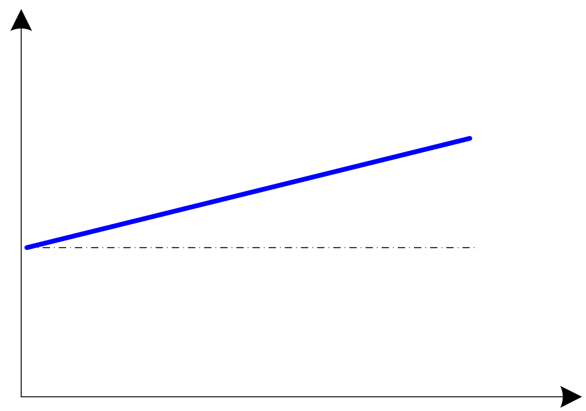
- Highway Resurfacing Projects
- Pavement Analysis:
  - Present Serviceability Index (PSI): 0~5
  - Restore serviceability level (*Pm*) to a threshold serviceability level (*Pt*) cyclically
  - Deterministic pavement deterioration process

$$P(t) = P_m - b \cdot t^a$$



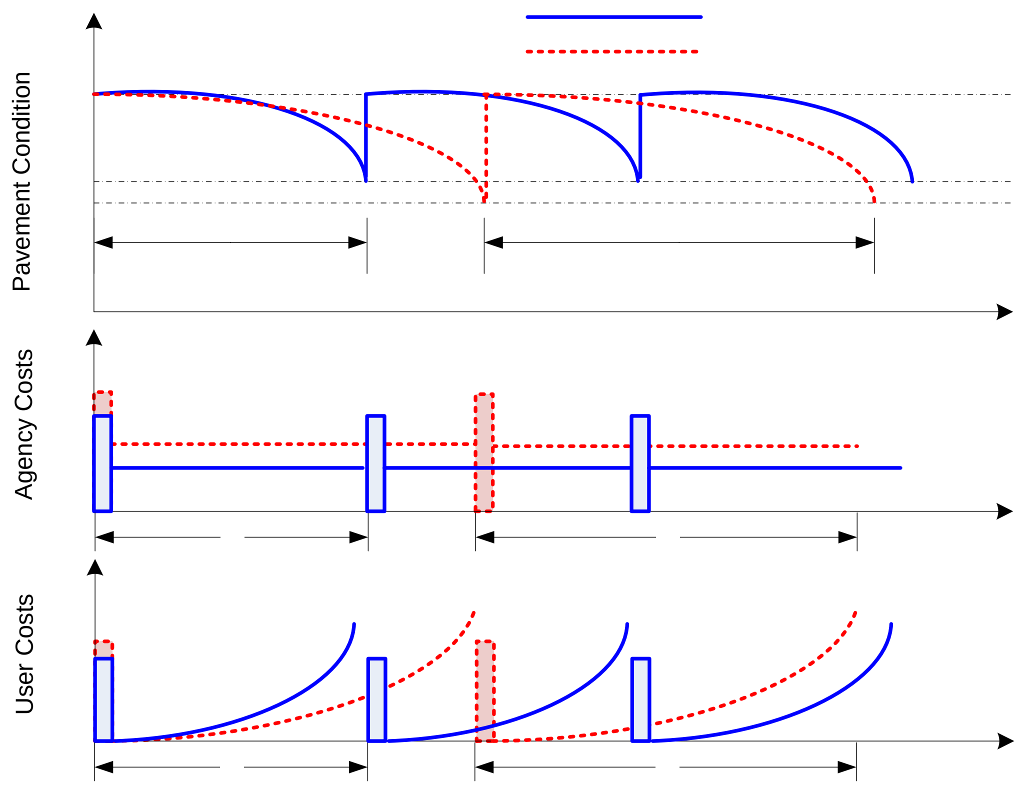
- Traffic Analysis:
  - Traffic is assumed to increase linearly over time

$$AADT(t) = AADT_m(1 + GR \cdot t)$$



- Resurfacing Strategy

the type of paving materials	
the thickness of the layers	*D*
the restored serviceability level	*Pm*
the threshold serviceability level	*Pt*
annual maintenance cost	*CLM*



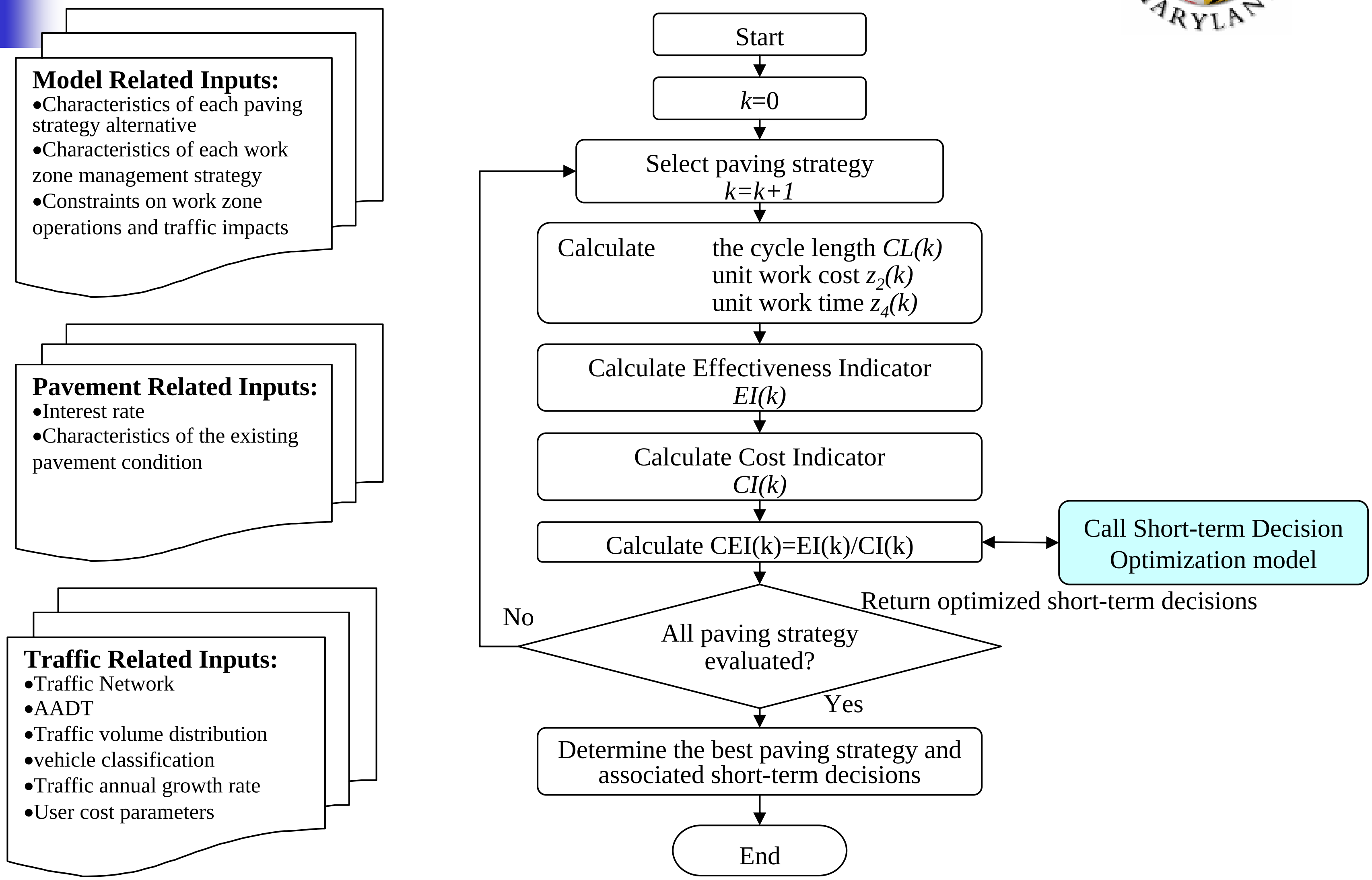
Derived Life Cycle Length

$$CL = \frac{1}{GR}\left(\sqrt{1 + 2 \cdot GR \cdot \frac{10^{A}}{B}} - 1\right)$$

A, B – Obtained from AASHTO 1993 pavement design equation

GR – AADT Annual Growth Rate

Optimization Framework



Tradeoffs between Work Time and Cost

- Motivation
  - For congested highway sections it may be worth spending more than the minimum cost on resurfacing in order to significantly reduce lane closure times, and hence the motorist delays.
- Objective
  - Develop an analytical model that considers the work time vs. cost tradeoffs for road resurfacing projects.
- Characteristics of our model
  - Interaction of variable cost and variable time per work unit
  - Consideration of traffic on detour road
  - The closure length and work rate are optimized, thus also optimizing work duration

Tradeoffs: Model Formulation

- We extend previous models for optimizing work zone lengths and diversion rates by analytically incorporating tradeoffs between work duration and cost.
- Construction Cost and Duration of Work Zone

$$C_M = z_1 + z_2 L$$

(Construction Cost)

$$D = z_3 + z_4 L$$

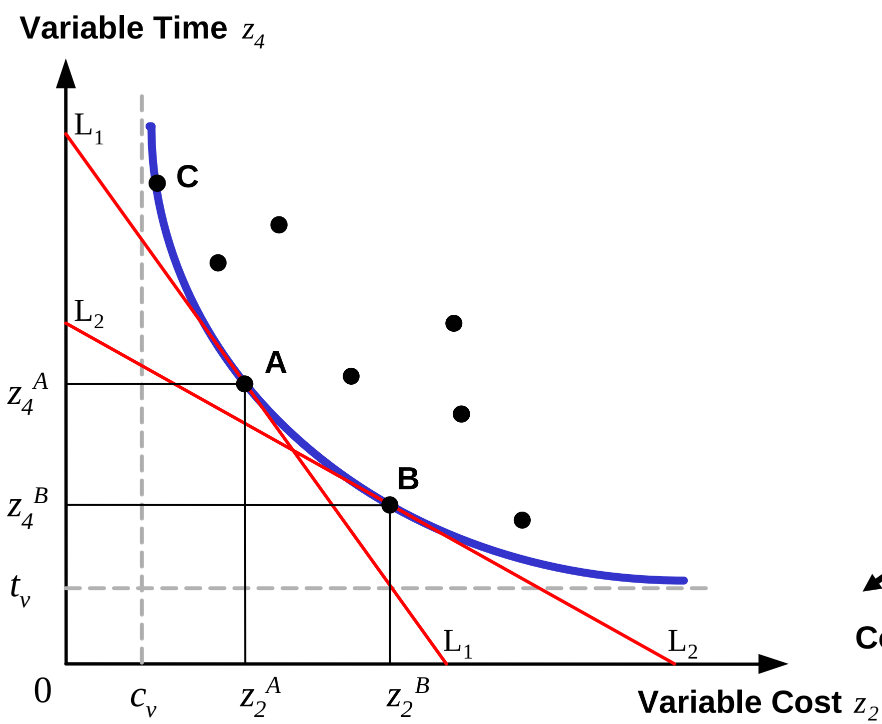
(Construction Duration)

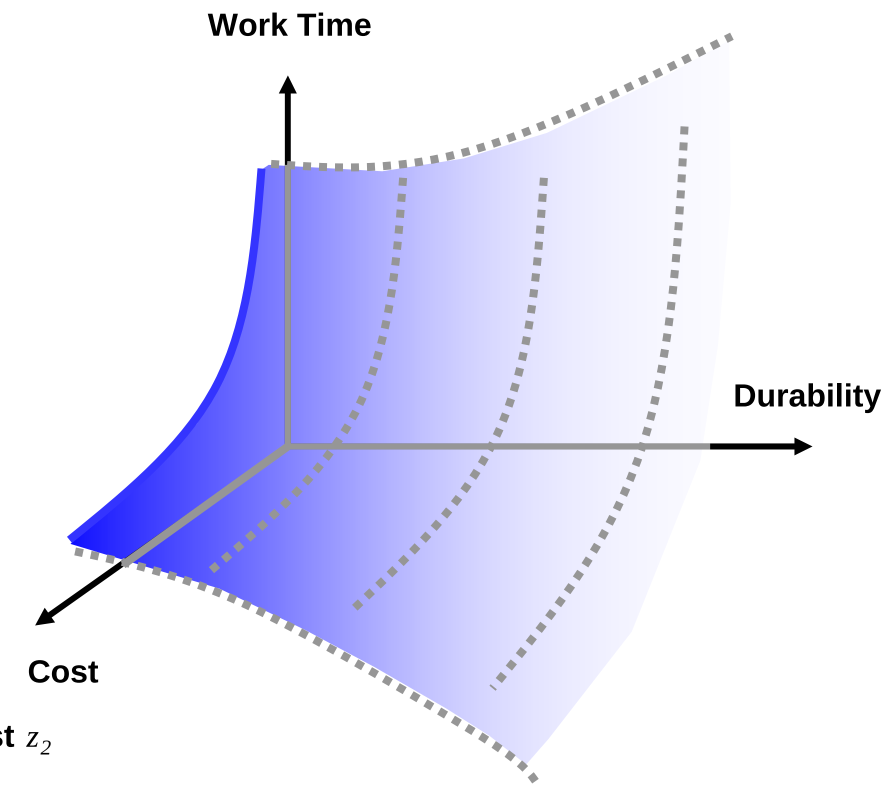
- Objective Function

$$C_T = \underbrace{C_m}_{\text{Construction Cost}} + \underbrace{(C_u^N + C_u^D) + C_{U3}}_{\text{User Delay Cost}} + \underbrace{(C_a^N + C_a^D)}_{\text{Accident Cost}}$$

(Construction Cost) (User Delay Cost) (Accident Cost)

Tradeoffs: Model Formulation (cont'd)





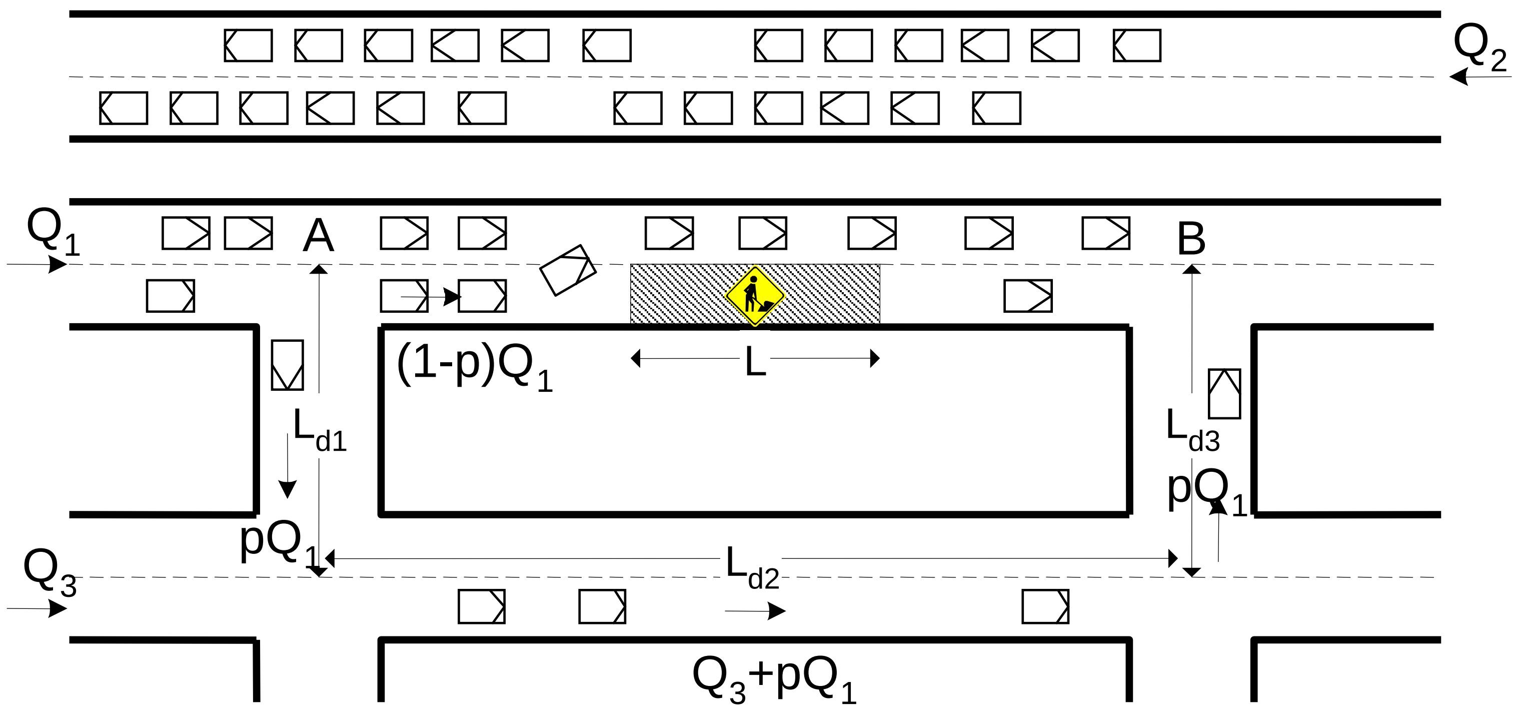
Tradeoffs: Model Formulation (cont'd)

- Time-Cost Tradeoff Function

$$(z_2 - c_v)(z_4 - t_v) = \overline{K} \quad \longrightarrow \quad z_4 = t_v + \frac{\overline{K}}{z_2 - c_v}$$

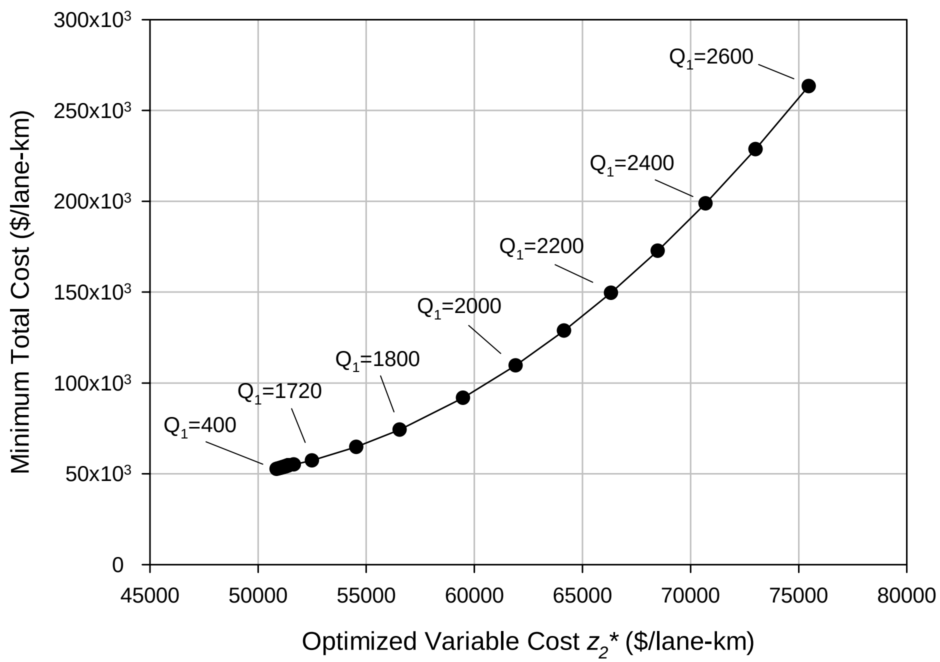
  - *Variable Duration* is represented as a function of *Variable Cost*
  - L_1 and L_2 represent two different ratios of time and cost.
  - L_1 has a lower time value (cost per time unit) than L_2
  - the contact points A and B indicate the optimal tradeoff combination of (z_2, z_4) for the time value lines L_1 and L_2, respectively.

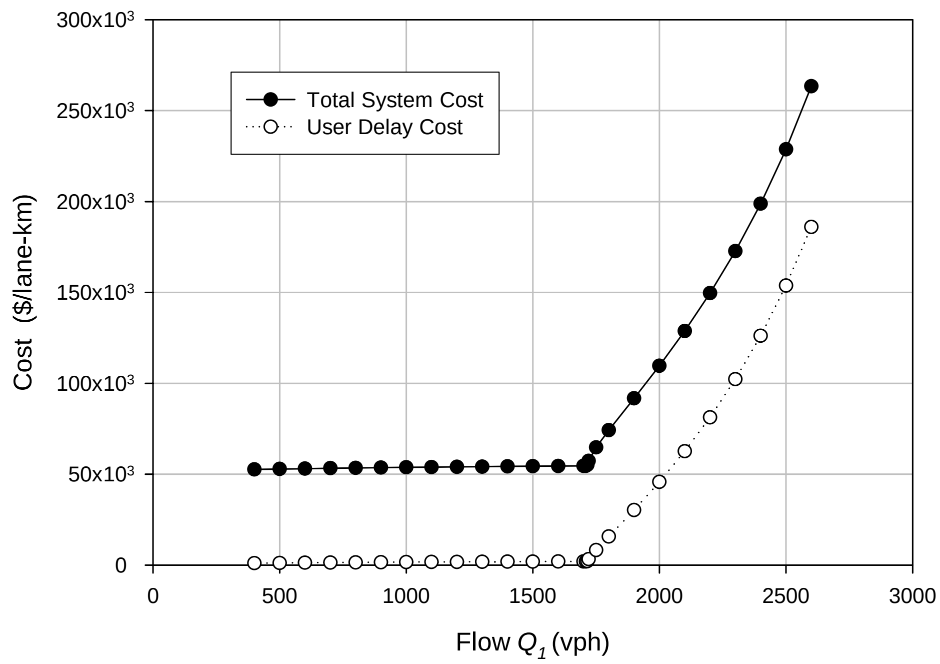
Tradeoffs: Target Network



Tradeoffs: Numerical Results (I)

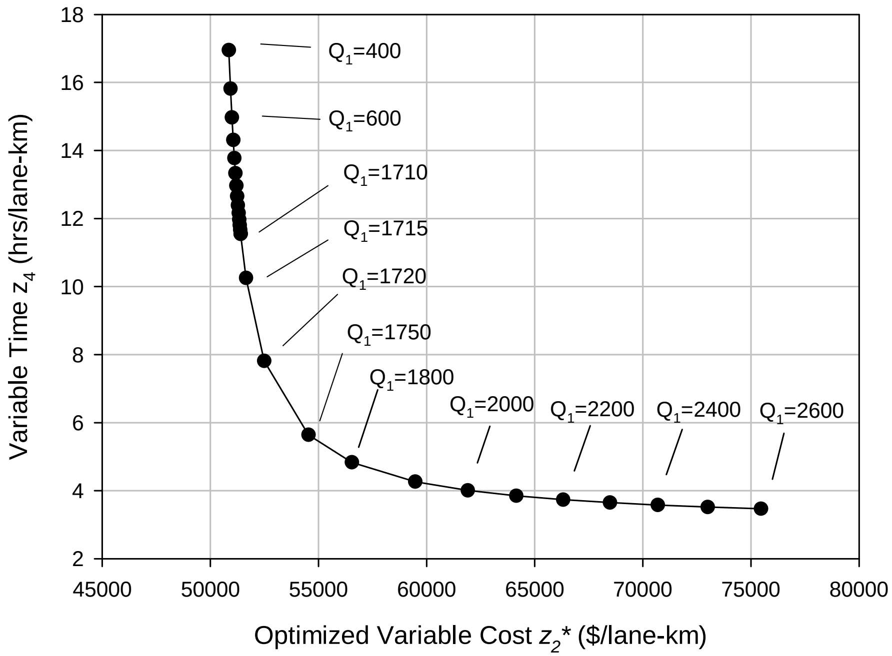
- Inflow vs. Optimized Variable Cost and Total System Cost



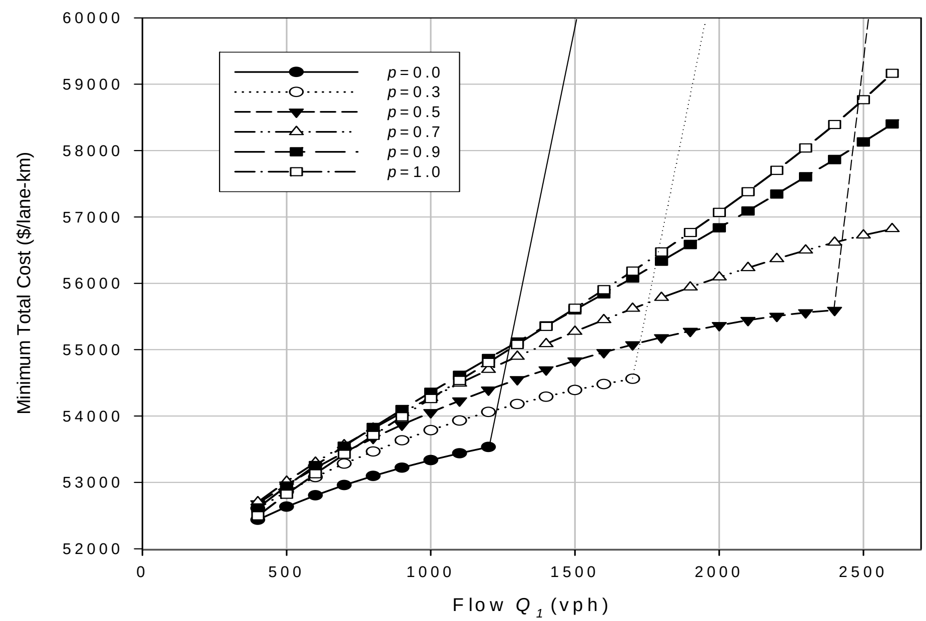


Tradeoffs: Numerical Results (II)

- Variable Cost vs. Variable Time

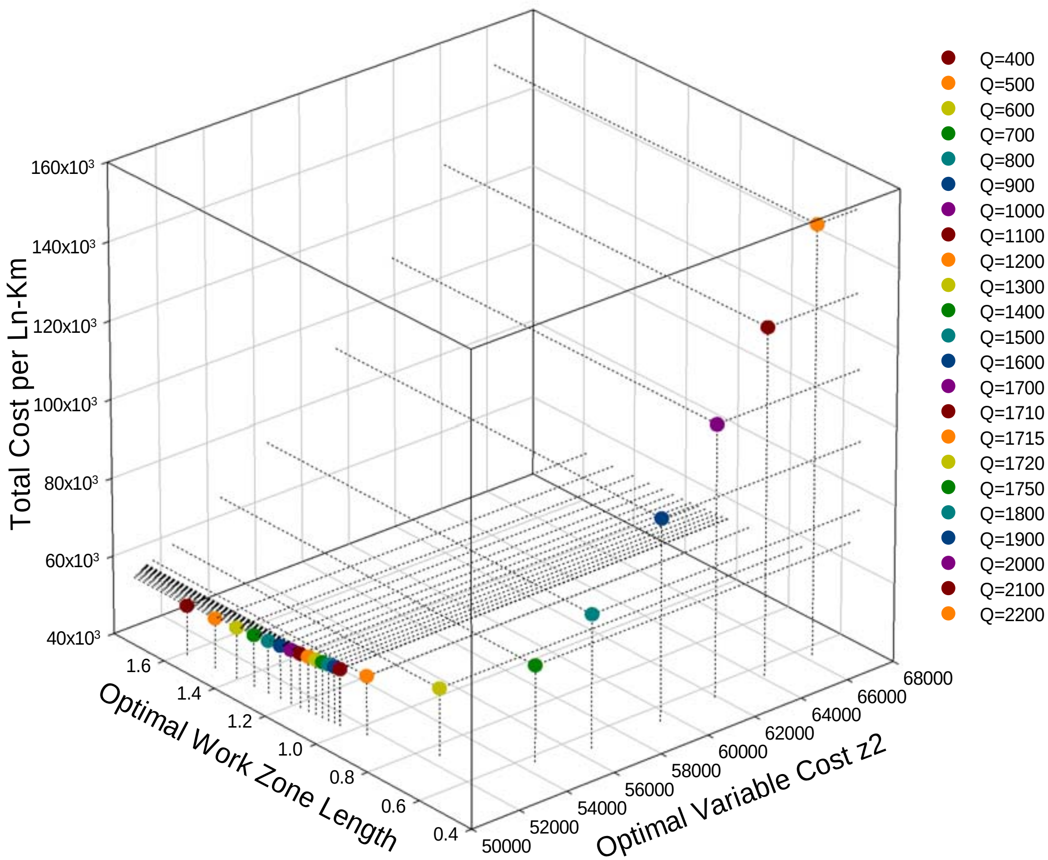


- Diversion Fraction *p*
  - The optimized *p** can be obtained by analyzing the envelope of the lowest total cost curves.



Tradeoffs: Major Findings

- When a queue occurs, the optimal work rate parameter z_2* increases rapidly to minimize cost. Employing a more expensive but faster construction method can help minimize the total cost.
- When the time-cost tradeoff is incorporated in the optimization, the optimal zone length *L** does not always decrease as the inflow increases; that length is jointly optimized with z_2 based on several input parameters.

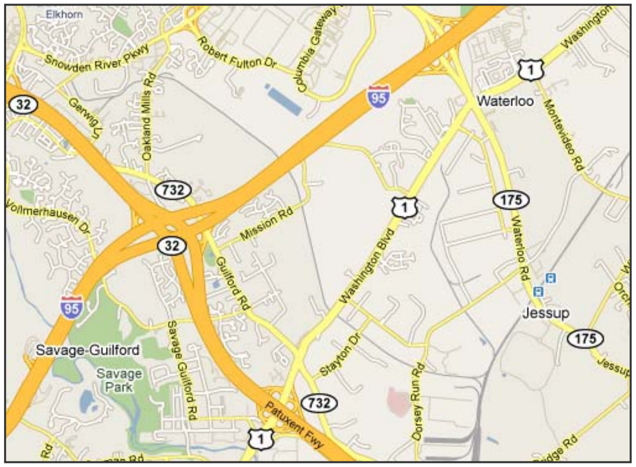


5. Case Studies

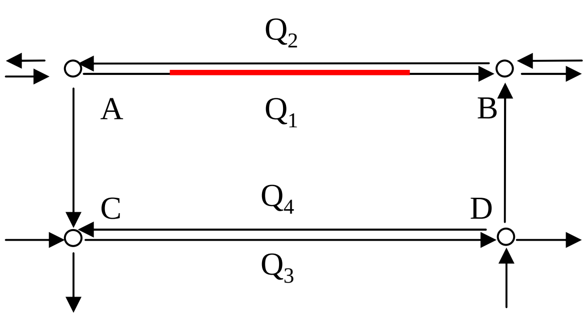
- Case Study 1
  - Optimization of Short-term Decisions based on Analytical Model
- Case Study 2
  - Joint Optimization of Short-term and Long-term Decisions based on Analytical Model
- Case Study 3
  - Optimization of Short-term Decisions based on Simulation Model

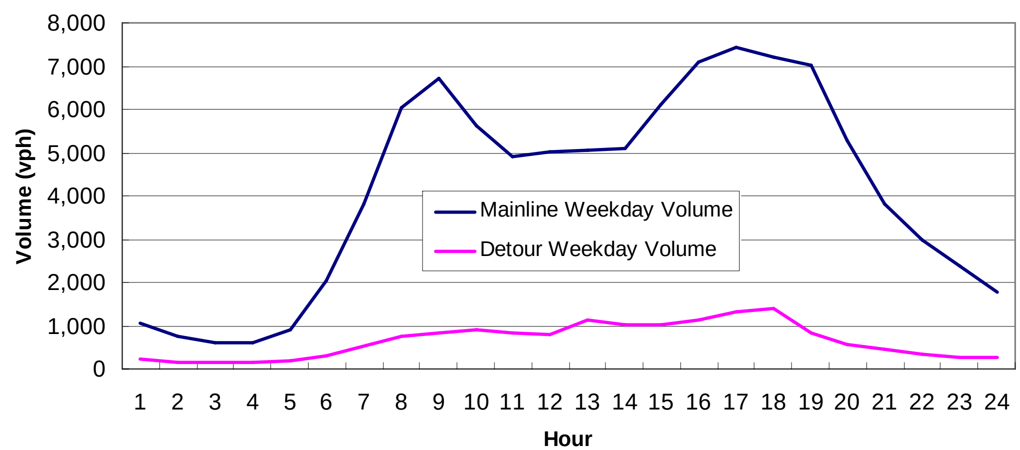
Case Study 1

- Test Network



Link	Length (mile)	# of Lanes (#)	Capacity (vphpl)	Free Flow Speed (mph)
AB/BA	3.1	4	2,200	65
AC	1.8	2	1,900	55
CD/DC	2.76	2	1,900	40
DB	0.6	3	1,900	55





Mainline AADT =99,314 Detour AADT =15,501

Critical Inputs

- Cyclic Period: Typical Weekday (16:00 pm – 16:00 pm next day)
- Candidate Strategies

Strategy Type 1: Lane closure configuration

Alt #	*Description*	N_W	N_a	N_c
1	Single Lane Closure	1	0 (use shoulder)	0
2	Double Lane Closure	2	0 (use shoulder)	0

Strategy Type 2: Accelerated construction

Alt #	*Description*	Δz_1	Δz_2	Δz_3	Δz_4
1	Normal work rate	0%	0%	0%	0%
2	Medium work rate	0%	+10%	0%	-15%
3	High work rate	0%	+20%	0%	-30%

Strategy Type 3: Detour strategy

Alt #	*Description*	*Behavior Model*	β_1 *($/zone)*	β_2 *($/hr)*
1	No detour control	-	0*	0*
2	Advanced detour control	SO/RC/UE	500	200

Strategy Type 4: Merge control system

Alt #	*Description*	*Capacity Change*	β_1*($/zone)*	β_2*($/hr)*
1	No merge control	0%	0*	0*
2	Advanced merge control	+15%	100	50

- Convergence, Optimality, and Reliability Analysis
  - Test Scenarios (no detour control)
    - Scenario 1: high volume traffic level, high intensity work
    - Scenario 2: low volume traffic level, high intensity work
    - Scenario 3: high volume traffic level, low intensity work
    - Scenario 4: low volume traffic level, low intensity work

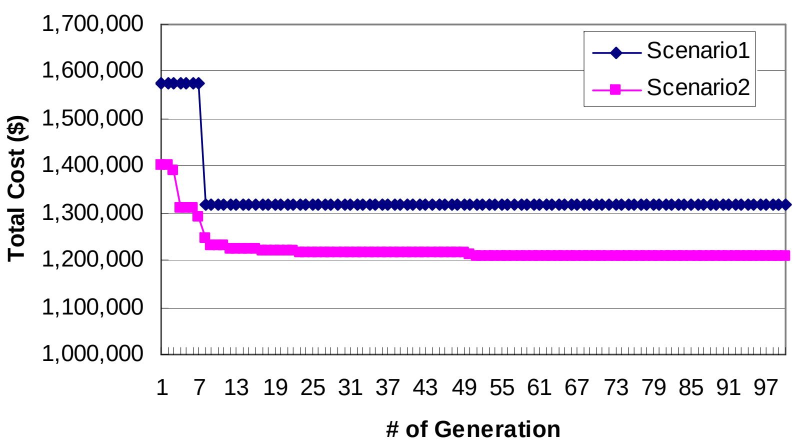
Traffic Level	Traffic Volume Multiplier	AADT
Low	0.6	59,588
High	1.0	99,314

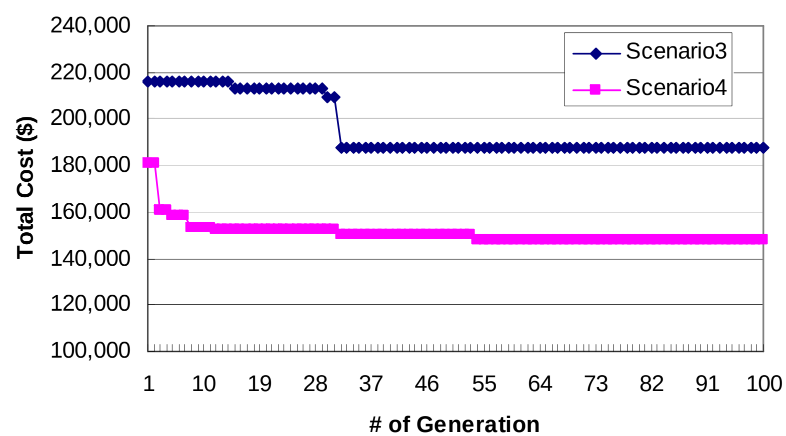
Work Intensity	Description	z_1	z_2	z_3	z_4
		\$/zone	*\$/lane.mile*	*hr/zone*	*hr/lane.mile*
Low	Pothole Patching	1000	10,000	2	4
High	Resurfacing	1000	110,000	2	8

Convergence Analysis

- Optimized Results

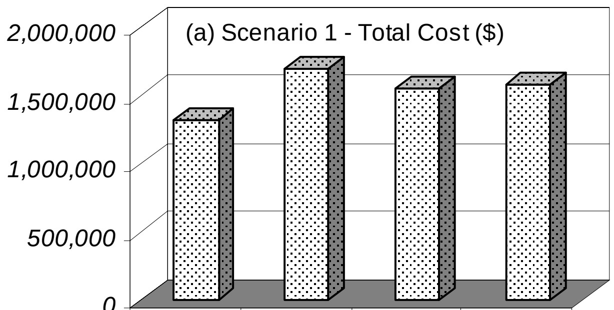
	# of Zones	Schedule	# of Closed Lanes	Work Rate	Merge Control
S1	1	20:30 -06:30	Double	Normal	Yes
S2	3	19:30-07:00 07:00-11:00 11:00015:00	Double Single Single	Normal Normal Normal	Yes Yes Yes
S3	1	21:00-06:00	Double	Normal	Yes
S4	2	20:00-07:00 07:00-14:00	Double Single	Normal Normal	No Yes



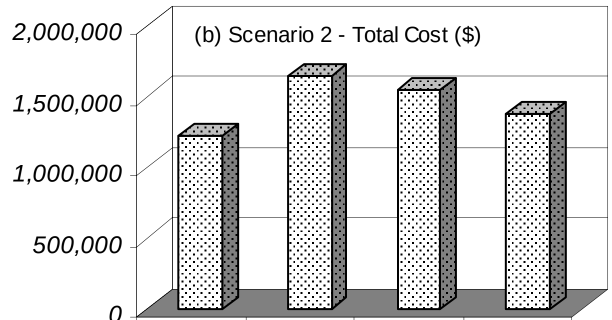


Optimality Analysis

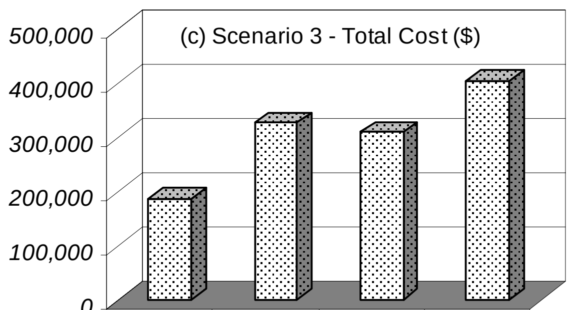
- Comparison with MD-SHA lane closure policies
  - C1: 19:00 -5:00, single lane closure
  - C2: 22:00-5:00, double lane closure
  - C3: 9:00-15:00 single lane closure, 22:00-5:00, double lane closure



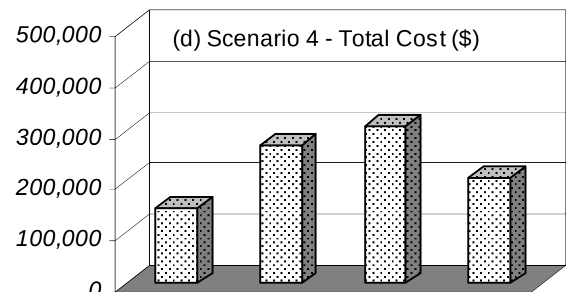
	S1-O	S1-C1	S1-C2	S1-C3
Total Cost ($)	1,318,080	1,699,100	1,549,930	1,581,340



	S2-O	S2-C1	S2-C2	S2-C3
Total Cost ($)	1,221,830	1,645,810	1,548,630	1,379,690



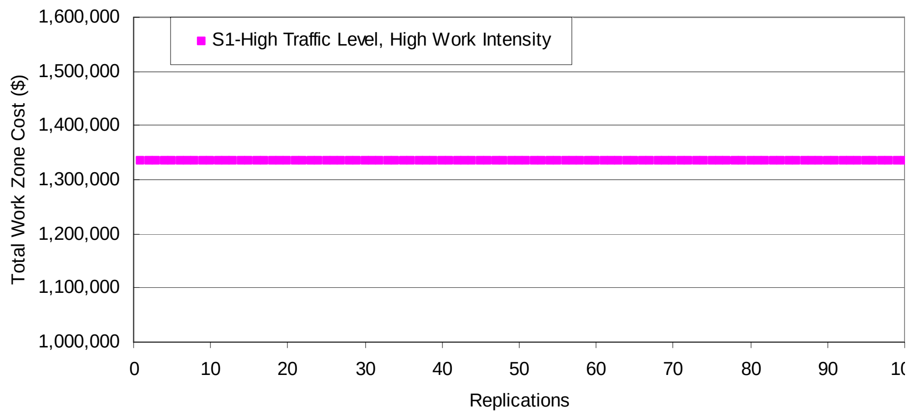
	S3-O	S3-C1	S3-C2	S3-C3
Total Cost ($)	187,948	327,997	310,661	405,562



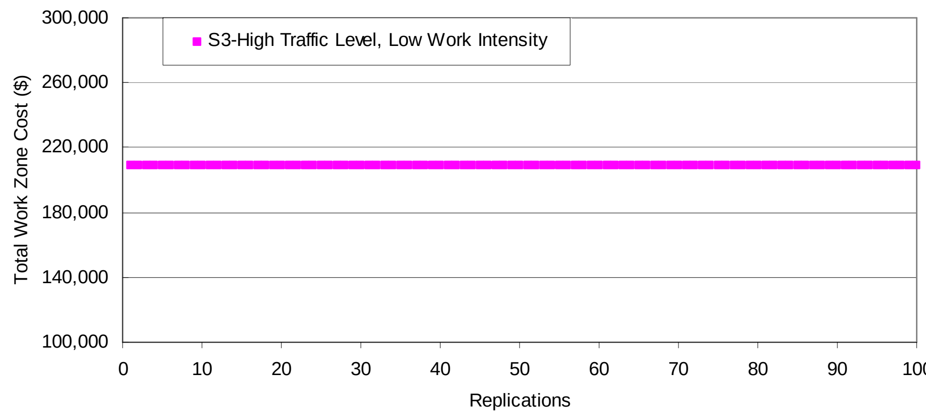
	S4-O	S4-C1	S4-C2	S4-C3
Total Cost ($)	147,923	273,737	309,203	208,523

Reliability Analysis

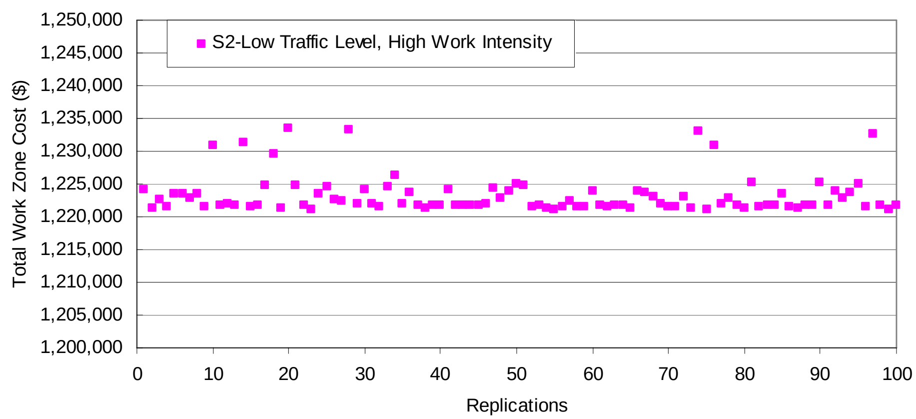
Optimized Results over 100 Replications



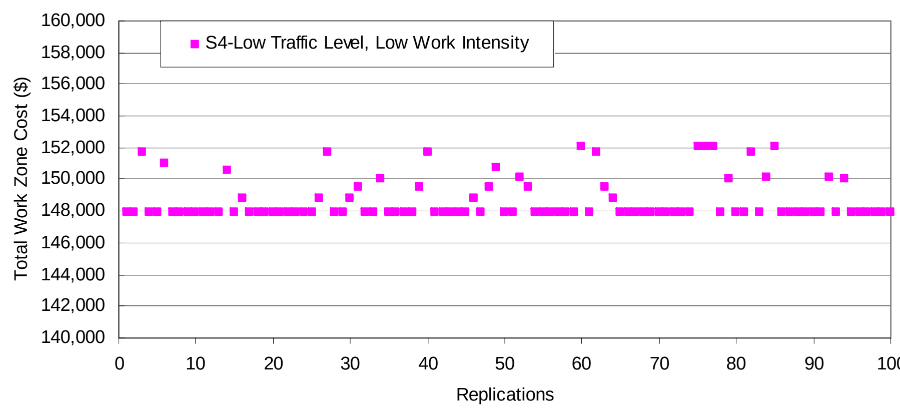
S1: CV =0.0%



S3: CV =0.0%



S2: CV =0.2%



S4: CV =0.9%

Sensitivity Analysis (Traffic Volume and Detour Model)

Baseline – Scenario 1

- Traffic Volume and Detour Model
  - Traffic Volume Multiplier: 0.2-2.0 (No Detour Control)

Traffic Level	# of periods*	Work Time	Zones	Str#1	Str#2	Str#3	Str#4	C_A	C_U	C_T
	#	hr/ period	#	Lane Closure	Work Rate	Detour	Merge Control	$	$	$
0.2	4	24	16:00-16:00	double	normal	no	no	1,059,490	8,024	1,067,514
0.4	4	24	16:00-04:00	double	normal	no	yes	1,069,056	17,691	1,086,747
			04:00-16:00	double	normal	no	yes			
0.6	6	17	19:00-07:30	double	normal	no	yes	1,134,023	23,349	1,157,372
			09:30-14:00	double	normal	no	yes			
0.8	7	15.5	20:00-07:00	double	normal	no	yes	1,213,767	17,645	1,231,413
			09:00-13:30	single	normal	no	yes			
1.0	10	10	20:30-06:30	double	normal	no	yes	1,295,360	22,719	1,318,079
1.2	12	8.5	21:30-06:00	double	normal	no	yes	1,384,023	10,768	1,394,791
1.4	13	8	22:00-06:00	double	normal	no	yes	1,427,200	9,773	1,436,973
1.6	14	7.5	22:30-06:00	double	normal	no	yes	1,472,593	18,683	1,491,276
1.8	12	6.5	23:00-05:30	double	fast	no	yes	1,634,227	10,362	1,644,589
2.0	16	5.5	23:30-05:00	double	fast	no	yes	1,806,320	6,403	1,812,723

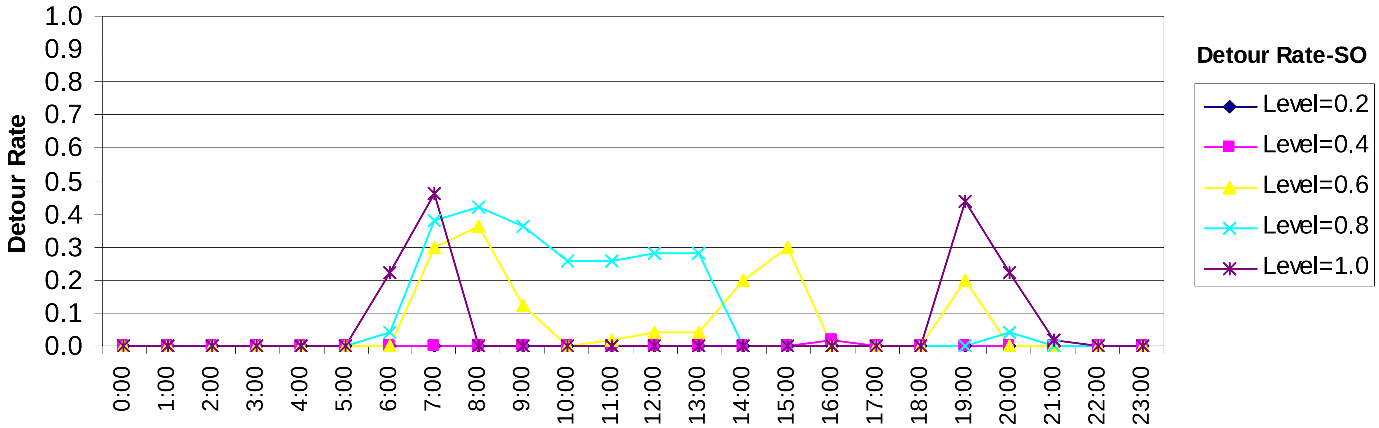
Sensitivity Analysis (Traffic Volume and Detour Model)

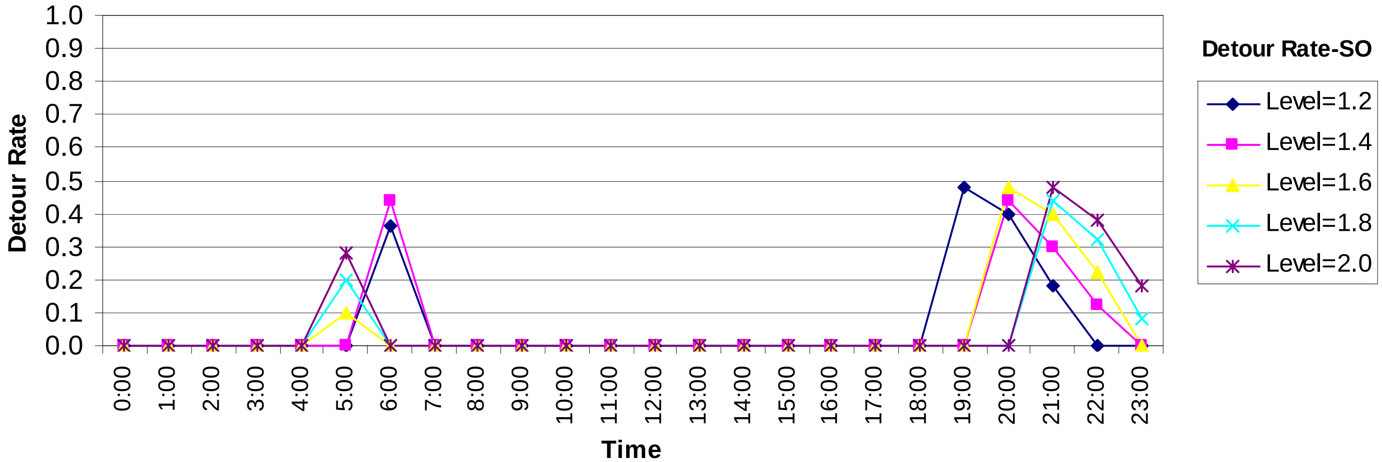
- Traffic Volume and Detour Model
  - Traffic Volume Multiplier: 0.2-2.0 (Detour Control – SO)

Traffic Level	***# of periods****	***Work Time***	***Zones***	***Str#1***	***Str#2***	***Str#3***	***Str#4***	C_A	C_U	C_T
	#	hr/ period	#	Lane Closure	Work Rate	Detour	Merge Control	$	$	$
0.2	4	24	16:00-16:00	double	normal	SO	no	1,077,990	8,024	1,086,020
0.4	4	24	16:00-16:00	double	normal	SO	yes	1,082,530	23,198	1,105,730
0.6	5	21	19:00-09:00	double	normal	SO	no	1,108,560	41,707	1,150,270
			09:00-16:00	double	normal	SO	yes			
0.8	5	18	20:00-14:00	double	normal	SO	yes	1,121,280	76,059	1,197,340
1	7	13	19:00-08:00	double	normal	SO	yes	1,199,860	44,203	1,244,070
1.2	8	12	19:00-07:00	double	normal	SO	yes	1,235,330	43,927	1,279,250
1.4	9	11	20:00-07:00	double	normal	SO	yes	1,252,080	34,563	1,286,640
1.6	10	10	20:00-06:00	double	normal	SO	yes	1,319,360	36,594	1,355,950
1.8	11	9	21:00-06:00	double	normal	SO	yes	1,362,210	27,878	1,390,088
2	11	9	21:00-06:00	double	normal	SO	yes	1,368,240	34,871	1,403,110

Sensitivity Analysis (Traffic Volume and Detour Model)

- Traffic Volume and Detour Model
  - Traffic Volume Multiplier: 0.2-2.0 (Detour Rate – SO)





Sensitivity Analysis (Traffic Volume and Detour Model)

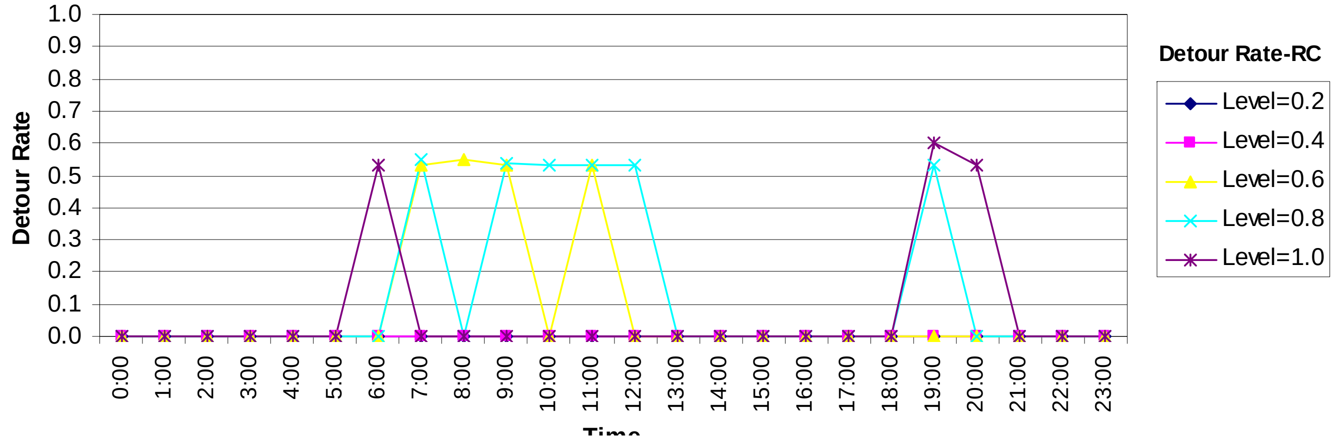
Traffic Volume and Detour Model

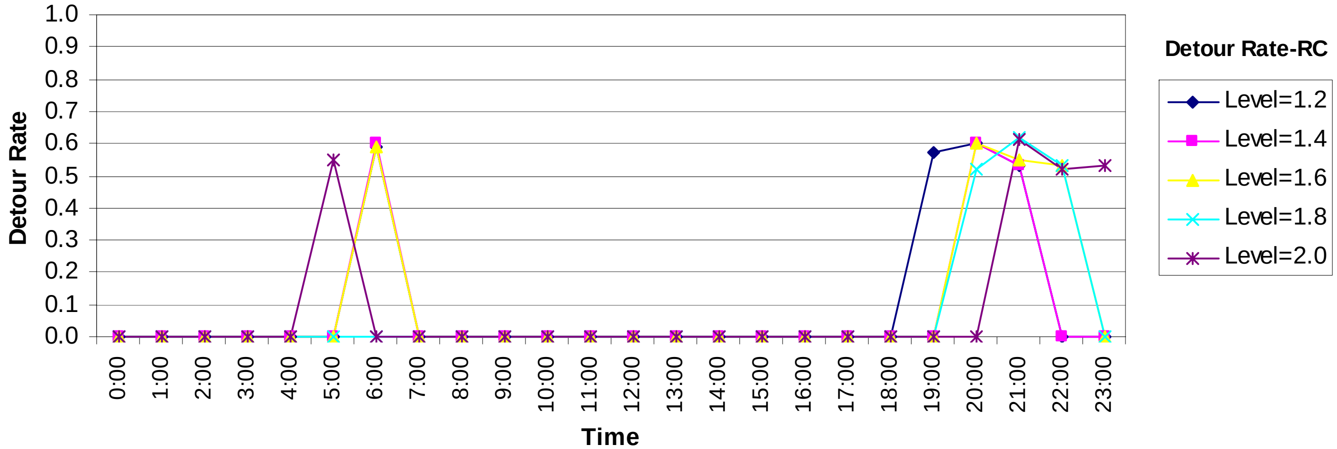
- Traffic Volume Multiplier: 0.2-2.0 (Detour Control – RC)

Traffic Level	***# of periods****	***Work Time***	***Zones***	***Str#1***	***Str#2***	***Str#3***	***Str#4***	C_A	C_U	C_T
	#	hr /period	#	Lane Closure	Work Rate	Detour	Merge Control	$	$	$
0.2	4	24	16:00-16:00	double	normal	RC	no	1,077,990	8,024	1,086,020
0.4	4	24	16:00-16:00	double	normal	RC	yes	1,082,530	23,069	1,105,600
0.6	5	17.5	19:30-13:00	double	normal	RC	no	1,119,770	53,013	1,172,790
0.8	6	17	19:00-08:00	double	normal	RC	yes	1,158,010	57,719	1,215,730
			09:00-13:00	double	normal	RC	yes			
1	7	12	19:00-07:00	double	normal	RC	yes	1,235,330	31,833	1,267,160
1.2	8	12	19:00-07:00	double	normal	RC	yes	1,235,330	59,255	1,294,580
1.4	9	11	20:00-07:00	double	normal	RC	yes	1,275,120	41,431	1,316,550
1.6	10	10	20:00-07:00	double	normal	RC	yes	1,275,120	64,758	1,339,880
1.8	11	9	20:30-05:30	double	normal	RC	yes	1,368,240	46,185	1,414,420
2	11	9	21:00-06:00	double	normal	RC	yes	1,362,210	48,811	1,411,020

Sensitivity Analysis (Traffic Volume and Detour Model)

- Traffic Volume and Detour Model
  - Traffic Volume Multiplier: 0.2-2.0 (Detour Rate – RC)





Sensitivity Analysis (Traffic Volume and Detour Model)

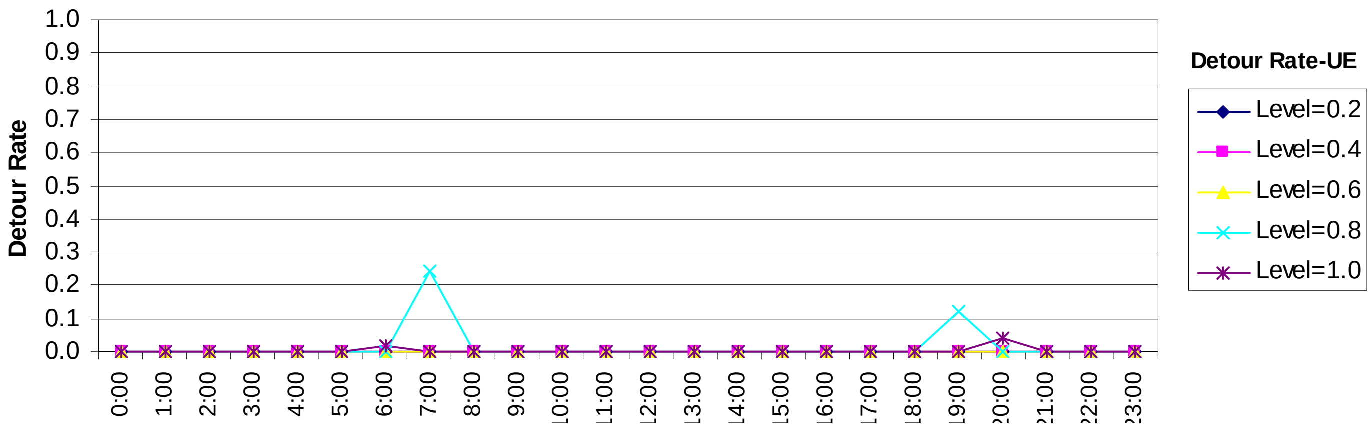
Traffic Volume and Detour Model

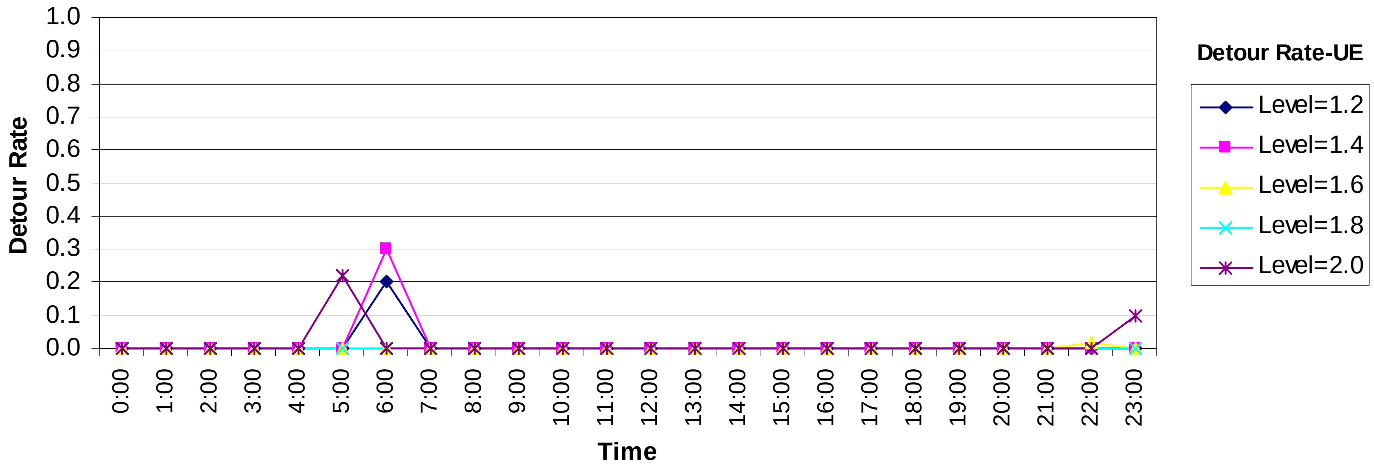
- Traffic Volume Multiplier: 0.2-2.0 (Detour Control – UE)

Traffic Level	***# of periods****	***Work Time***	***Zones***	***Str#1***	***Str#2***	***Str#3***	***Str#4***	C_A	C_U	C_T
	#	hr/ period	#	Lane Closure	Work Rate	Detour	Merge Control	$	$	$
0.2	4	24	16:00-16:00	double	normal	UE	no	1,077,990	8,024	1,086,020
0.4	4	24	16:00-16:00	double	normal	UE	yes	1,082,530	23,069	1,105,600
0.6	5	17	19:30-07:30	double	normal	UE	yes	1,160,010	23,349	1,183,360
			09:30-14:00	double	normal	UE	yes			
0.8	8	12	19:30-07:30	double	normal	UE	yes	1,235,330	28,252	1,263,580
1	10	10	20:30-06:30	double	normal	UE	yes	1,319,360	20,257	1,339,620
1.2	11	9	21:30-06:30	double	normal	UE	yes	1,368,240	17,858	1,386,100
1.4	12	8.5	22:00-06:30	double	normal	UE	yes	1,410,010	18,996	1,429,010
1.6	14	7.5	22:30-06:00	double	normal	UE	yes	1,500,520	17,684	1,518,210
1.8	14	6.5	23:00-05:30	double	normal	UE	yes	1,625,630	10,259	1,635,890

Sensitivity Analysis (Traffic Volume and Detour Model)

- Traffic Volume and Detour Model
  - Traffic Volume Multiplier: 0.2-2.0 (Detour Rate – UE)



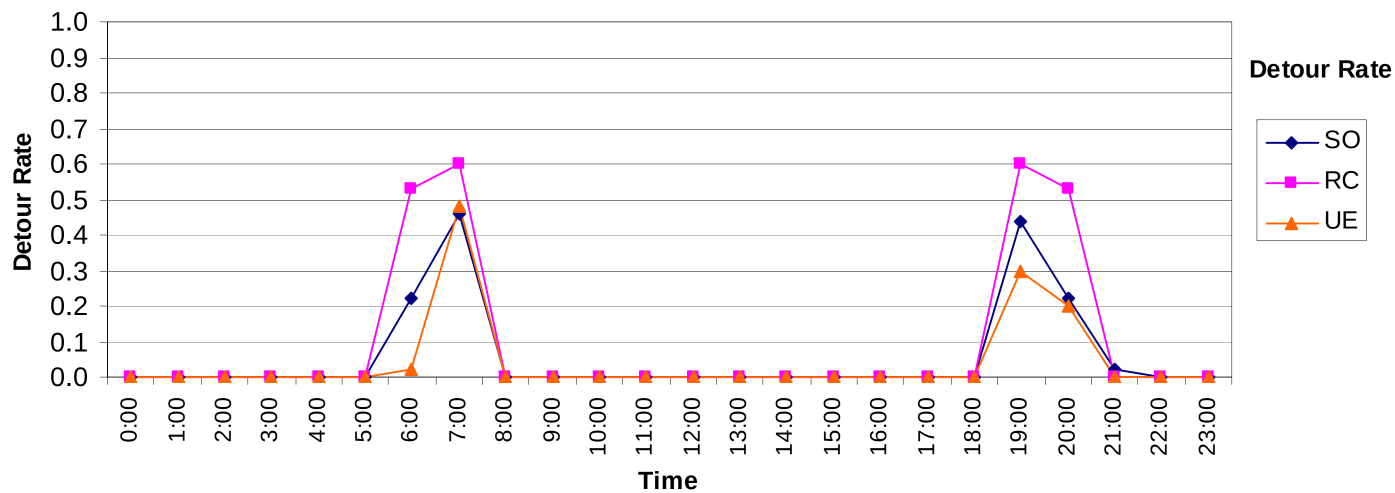


Sensitivity Analysis (Traffic Volume and Detour Model)

Comparison of Different Detour Models

Traffic Level	# of Periods	WorkTime	# of Zones	Str#1	Str#2	Str#3	Str#4
	#	hr/period	#	Lane Closure	Work Rate	Detour	Merge Control
1	7	13	19:00-08:00	double	normal	-	yes

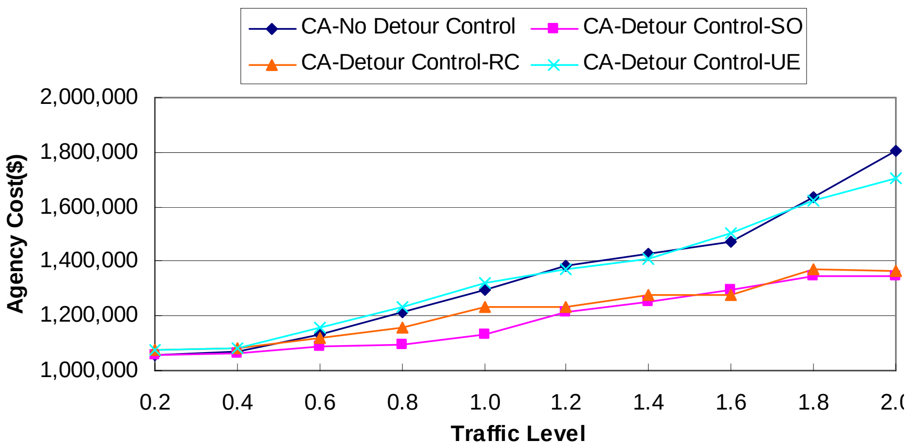
	C_M	Cs	C_I	C_A	C_D	C_V	C_E	C_U	C_T
N/A	1,062,980	5,236	110,000	1,178,220	320,076	18,629	27,722	366,427	1,544,650
SO	1,062,980	26,880	110,000	1,199,860	22,727	20,268	1,209	44,203	1,244,070
RC	1,062,980	26,880	110,000	1,199,860	28,136	27,610	547	56,294	1,256,160
UE	1,062,980	26,880	110,000	1,199,860	67,516	16,246	5,931	89,694	1,289,560



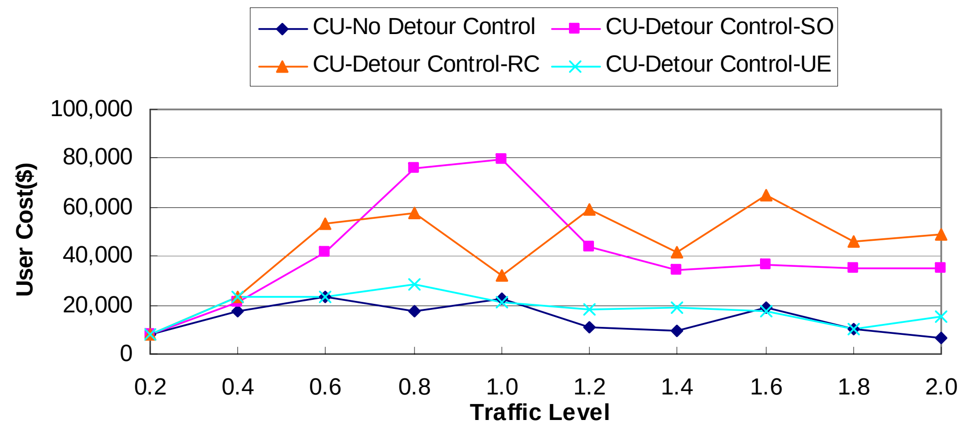
Sensitivity Analysis (Traffic Volume and Detour Model)

- Comparison of Different Detour Models

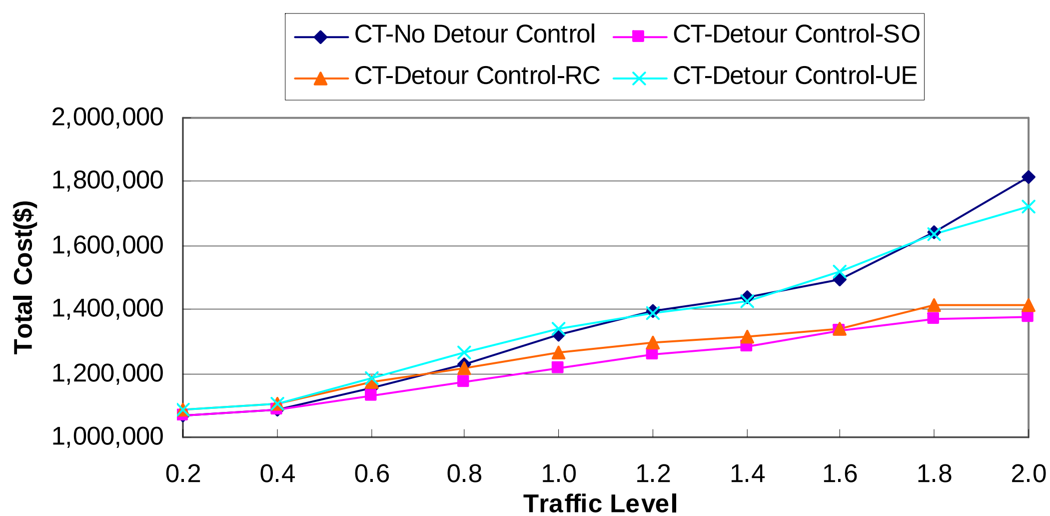
Agency Costs



User Costs



Total Costs



Sensitivity Analysis (Idling Cost)

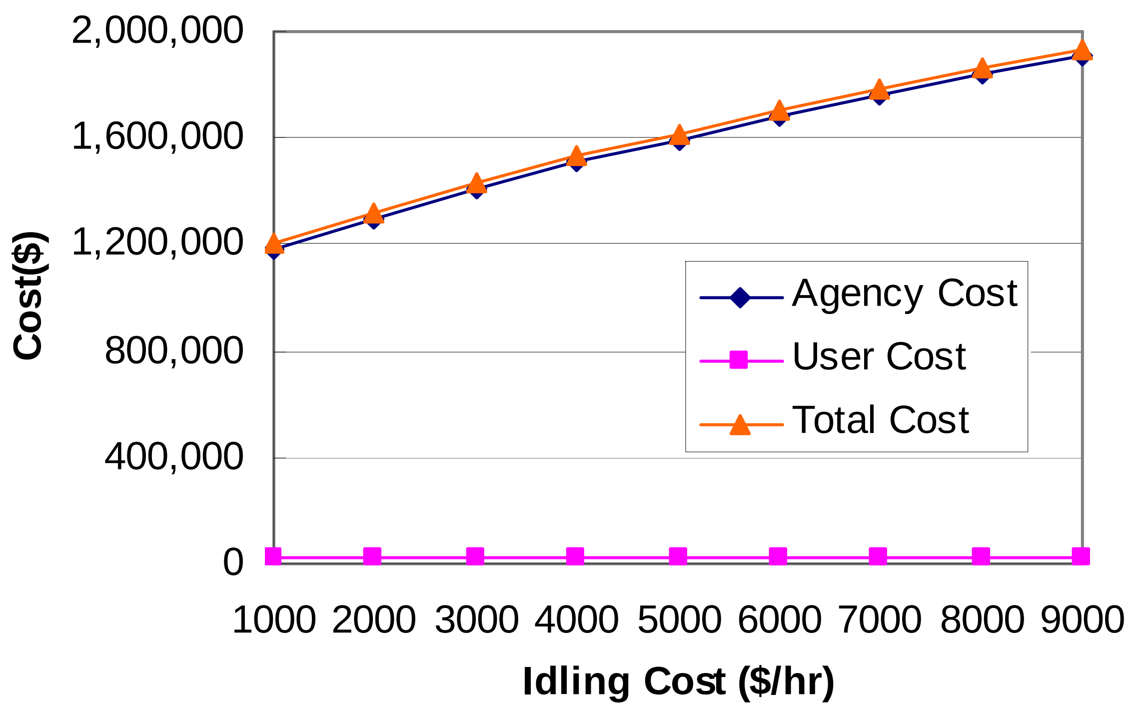
Baseline – Scenario 1

- Idling Cost: 1000 $/hr to 9000 $/hr

Idling Cost	# of periods*	Work Time	Zones	Str#1	Str#2	Str#3	Str#4	CA	CU	CT
$/hr	#	hr/ period	#	Lane Closure	Work Rate	Detour	Merge Control	$	$	$
1000	10	10	20:30-06:30	double	normal	no	yes	1,183,360	22,719	1,206,079
2000	10	10	20:30-06:30	double	normal	no	yes	1,295,360	22,719	1,318,079
3000	10	10	20:30-06:30	double	normal	no	yes	1,407,360	22,719	1,430,079
4000	8	10	20:30-06:30	double	medium	no	yes	1,509,888	23,078	1,532,966
5000	8	10	20:30-06:30	double	medium	no	yes	1,593,888	23,078	1,616,966
6000	8	10	20:30-06:30	double	medium	no	yes	1,677,888	23,078	1,700,966
7000	8	10	20:30-06:30	double	fast	no	yes	1,761,888	23,078	1,784,966
8000	7	10	20:30-06:30	double	fast	no	yes	1,837,952	23,335	1,861,287
9000	7	10	20:30-06:30	double	fast	no	yes	1,907,952	23,335	1,931,287

Sensitivity Analysis (Idling Cost)

- Idling Cost: 1000 $/hr to 9000 $/hr



Sensitivity Analysis (Project Deadline)

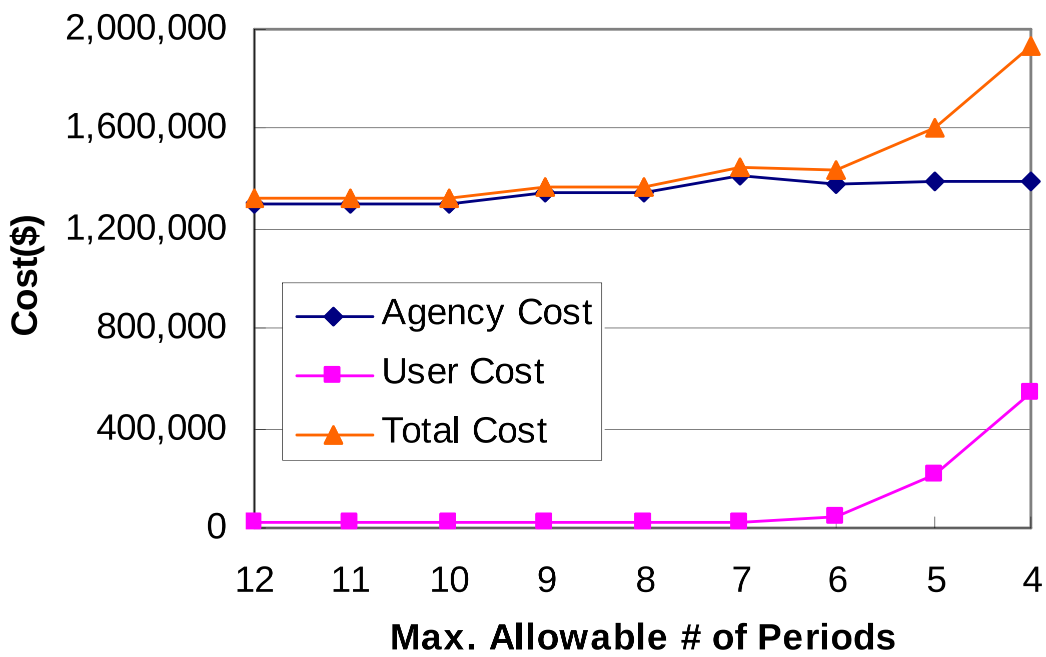
Baseline – Scenario 1

- Project Deadline: 12 days – 4 days

Max # of periods	***# of periods****	***Work Time***	***Zones***	***Str#1***	***Str#2***	***Str#3***	***Str#4***	***CA***	***CU***	***CT***
#	#	hr/ period	#	Lane Closure	Work Rate	Detour	Merge Control	$	$	$
12-10	10	10	20:30-06:30	double	normal	no	yes	1,295,360	22,719	1,318,080
9	8	10	20:30-06:30	double	medium	no	yes	1,341,890	23,078	1,364,970
8	8	10	20:30-06:30	double	medium	no	yes	1,341,890	23,078	1,364,970
7	7	10	20:30-06:30	double	fast	no	yes	1,417,950	23,335	1,441,290
6	6	11	20:00-07:00	double	fast	no	yes	1,381,060	49,132	1,430,190
5	5	15.5	19:30-07:00	double	fast	no	yes	1,384,270	217,517	1,601,790
			10:00-14:00	single	fast	no	yes			
4	4	17.5	19:00-07:30	double	fast	no	yes	1,385,430	541,280	1,926,710
			09:00-14:30	single	fast	no	yes			

Sensitivity Analysis (Project Deadline)

- Project Deadline: 12 days – 4 days



Sensitivity Analysis (Work Zone Fixed Setup Time)

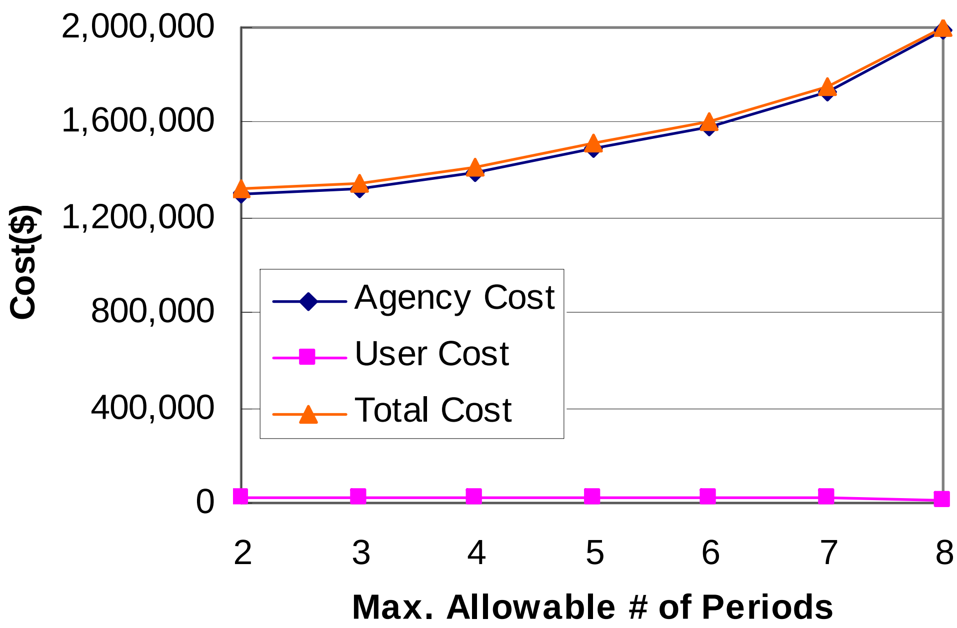
Baseline – Scenario 1

- Work Zone Fixed Setup Time : 2 hr/zone – 8 hr/zone

z3	***# of periods****	***Work Time***	***Zones***	***Str#1***	***Str#2***	***Str#3***	***Str#4***	***CA***	***CU***	***CT***
hr/zone	#	hr/ period	#	Lane Closure	Work Rate	Detour	Merge Control	$	$	$
2	10	10	20:30-06:30	double	normal	no	yes	1,295,360	22,719	1,318,080
3	11	10	20:30-06:30	double	normal	no	yes	1,325,550	22,540	1,348,090
4	13	10	20:30-06:30	double	normal	no	yes	1,384,480	22,360	1,406,840
5	13	10	20:30-06:30	double	medium	no	yes	1,489,260	22,405	1,511,670
6	16	10	20:30-06:30	double	medium	no	yes	1,578,180	22,181	1,600,360
7	21	10	20:30-06:30	double	medium	no	yes	1,726,370	21,957	1,748,320
8	22	11.5	19:30-07:00	single	medium	no	yes	1,988,750	14,121	2,002,880

Sensitivity Analysis (Work Zone Fixed Setup Time)

- Work Zone Fixed Setup Time : 2 hr/zone – 8 hr/zone



Case Study 1- Findings

- The proposed optimization algorithm converges reliably to near-optimal solutions
- Efficient lane closure tactics (e.g. scheduling work zone in appropriate time windows) can significantly reduce the work zone costs
- Deployment of traffic impact management strategies, such as merge control and detour control system, can be beneficial and cost effective, especially on projects with high resource/labor idling cost, longer fixed work zone setup time, and tighter deadline.
- Detour control has great potential to mitigate the traffic impact and reduce project cost by efficiently utilizing spare capacity in a road network. Its effectiveness depends highly on road users’ detour behavior as well as the physical and traffic characteristics of the mainline and alternative routes.

Case Study 2

- The Same Test Network from Case Study 1
- Baseline Parameters
  - Interest Rate: I =4%
  - Traffic Growth Rate: GR =3%
- Candidate Resurfacing Strategies

Paving Strategy	Strategy Description	Category	Overlay Thickness (inch)	P_m	P_t
1	Thin HMA Overlay	Light Rehabilitation	1.5	4.5	2.5
2	Thin HMA Overlay	Light Rehabilitation	2.0	4.5	2.5
3	Medium HMA Overlay	Moderate Rehabilitation	2.5	4.5	2.5
4	Medium HMA Overlay	Moderate Rehabilitation	3.0	4.5	2.5
5	Medium HMA Overlay	Moderate Rehabilitation	3.5	4.5	2.5
6	Thick HMA Overlay	Heavy Rehabilitation	4.0	4.5	2.5
7	Thick HMA Overlay	Heavy Rehabilitation	4.5	4.5	2.5

Critical Inputs

- Candidate Resurfacing Strategies

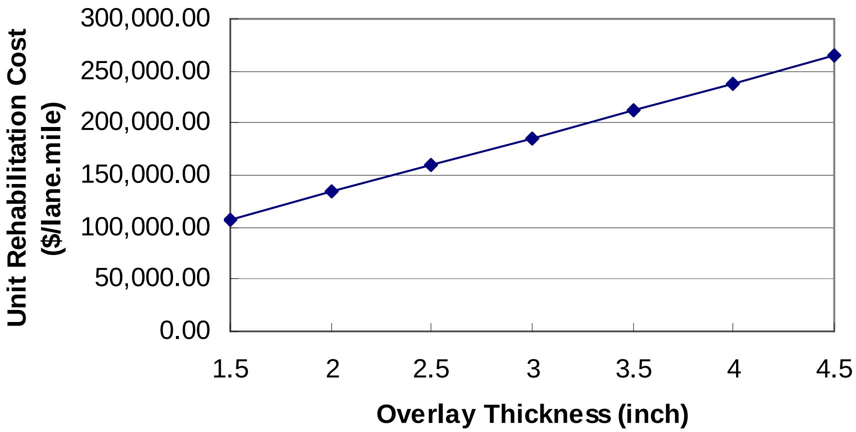
Paving strategy	z_1	z_2	z_3	z_4	***CLM***
#	$/lm	$/lm	hr/lm	hr/lm	$/lm-year
1	1000	78000	2	8.0	1000
2	1000	94000	2	10.4	1000
3	2000	110000	4	12.8	1000
4	2000	126000	4	15.2	1000
5	2000	142000	4	17.6	1000
6	4000	158000	6	20.0	1000
7	4000	174000	6	22.4	1000

$$z_2 = 30{,}000 + 52{,}000 \cdot Th$$

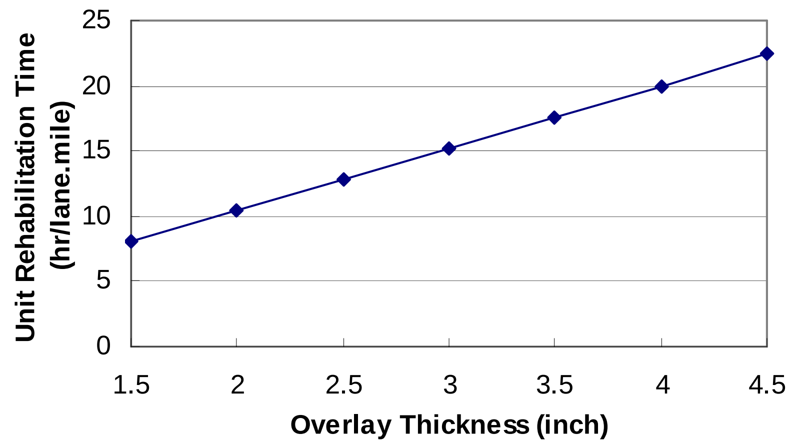
$$z_4 = 0.4 + 2.4 \cdot Th$$

$$CL = \frac{1}{GR}\left(\sqrt{1 + 2 \cdot GR \cdot \frac{10^A}{B}} - 1\right)$$

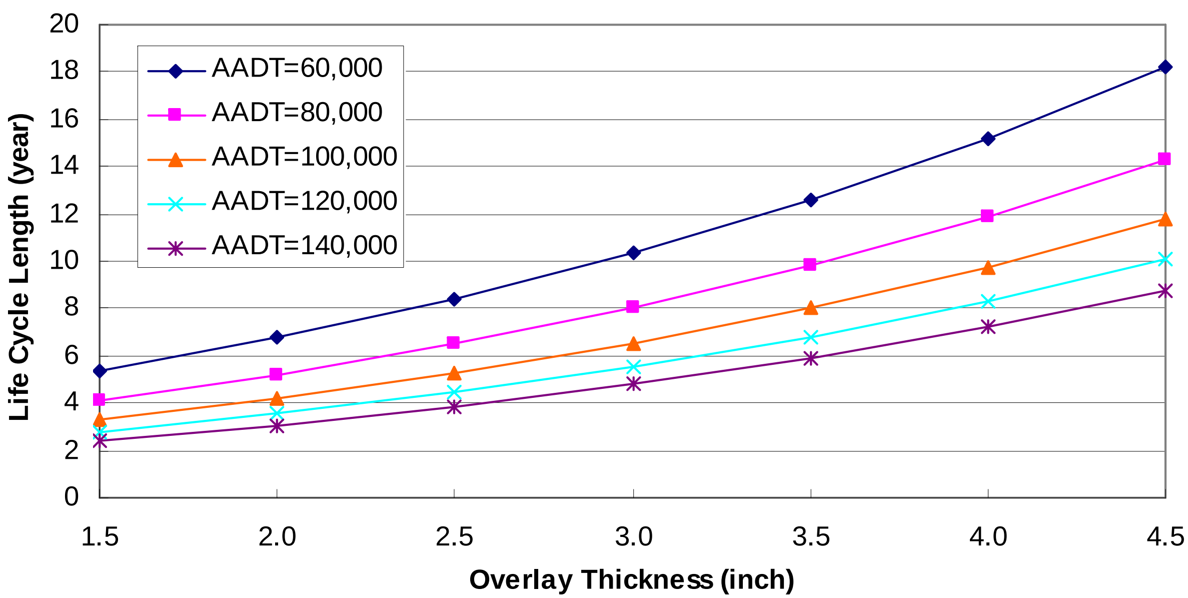
Z2



Z4



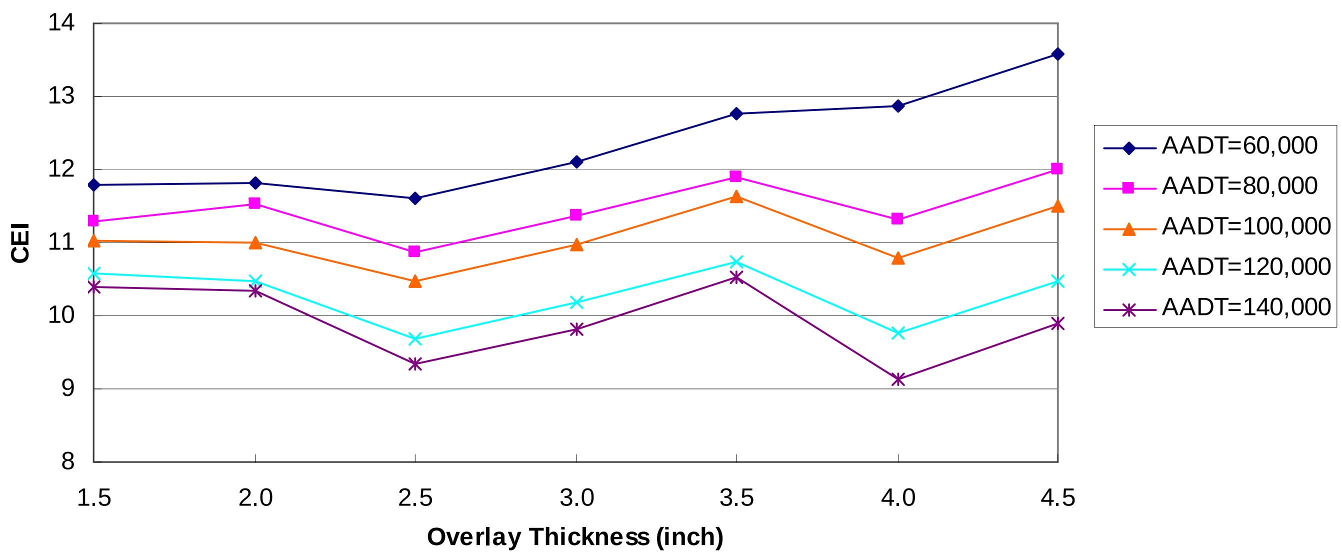
Life Cycle Length



Optimized Results

- No Detour Control in Work Zones

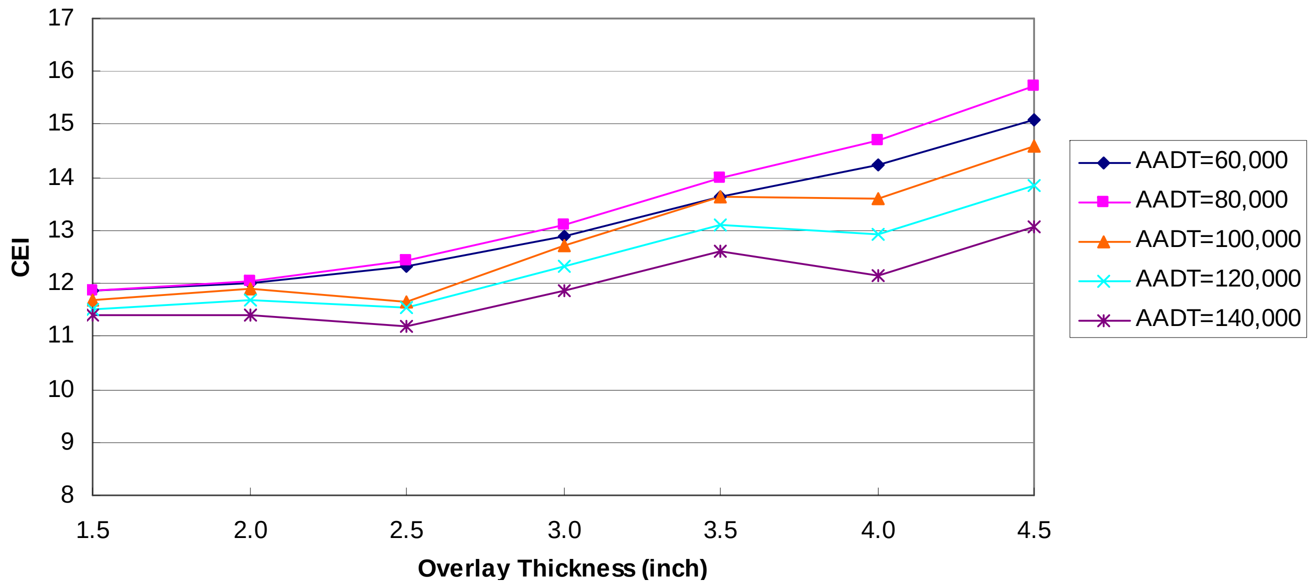
AADT	Optimal Overlay Thickness	Life Cycle Length	CI	*EI*	*CEI*
Vehicle/day	*inch*	*year*	-	-	-
60,000	4.5	18.17	287,240.35	21,152.44	13.58
80,000	4.5	14.28	366,656.43	30,570.08	11.99
100,000	3.5	8.03	425,503.73	36,613.86	11.62
120,000	3.5	6.81	502,874.63	46,879.50	10.73
140,000	3.5	5.91	580,072.93	55,121.38	10.52



Optimized Results

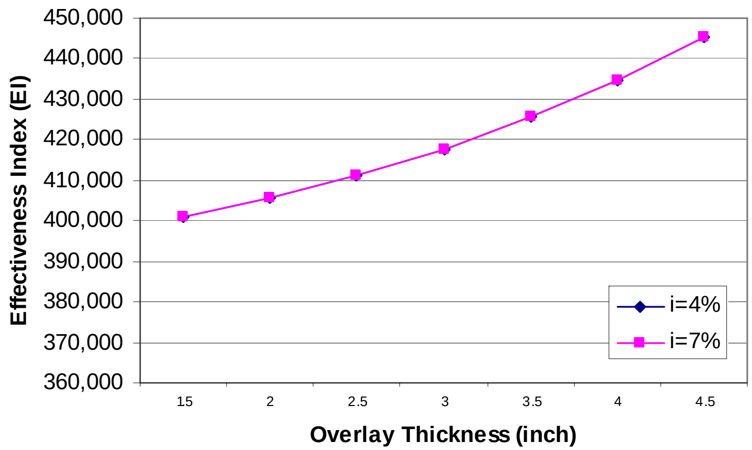
- SO Detour Control in Work Zones

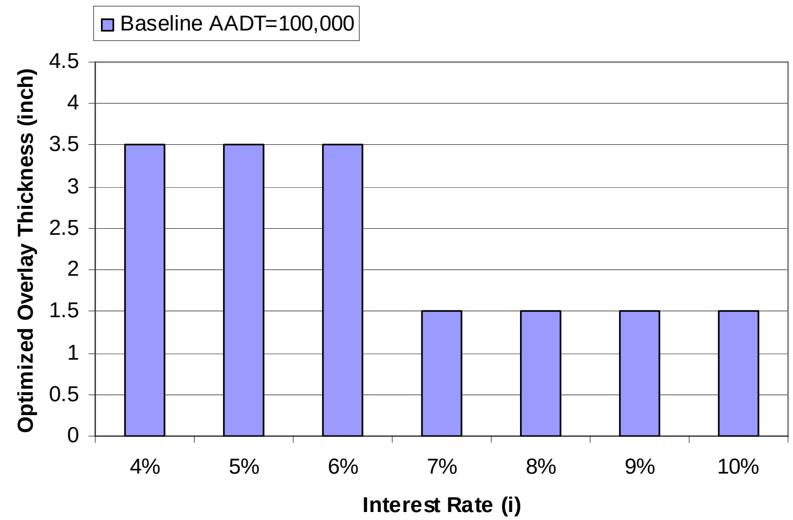
AADT	Optimal Overlay Thickness (inch)	Life Cycle Length (yr)	CI	*EI*	*CEI*
60,000	4.5	18.17	287,240.35	19,022.42	15.10
80,000	4.5	14.28	366,656.43	23,336.78	15.71
100,000	4.5	11.79	445,229.69	30,505.83	14.59
120,000	4.5	10.05	523,301.78	37,755.58	13.86
140,000	4.5	8.76	601,049.66	45,973.72	13.07

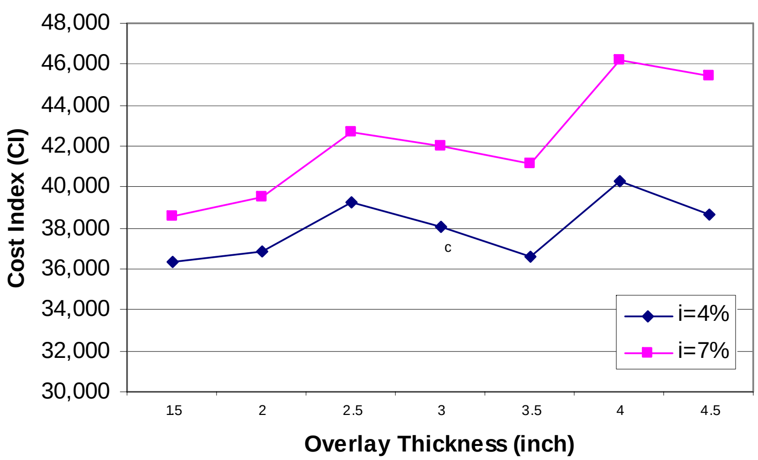


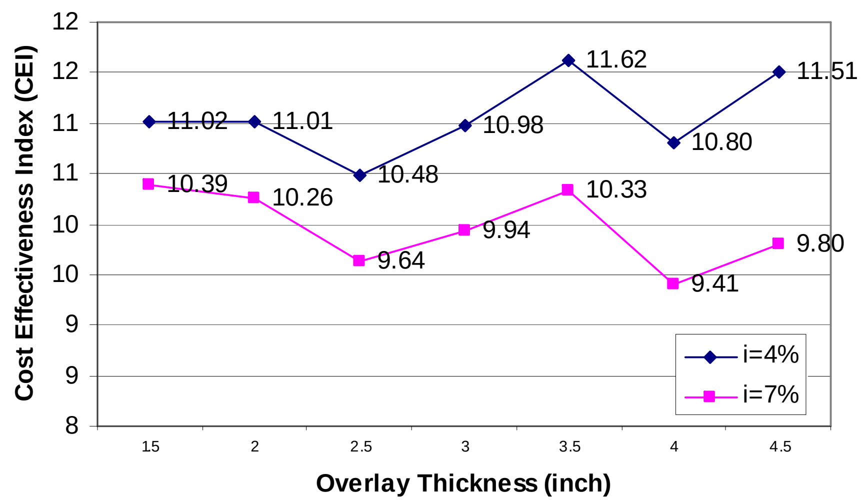
Sensitivity Analysis (Interest Rate)

- Interest Rate (i): 4% - 10%



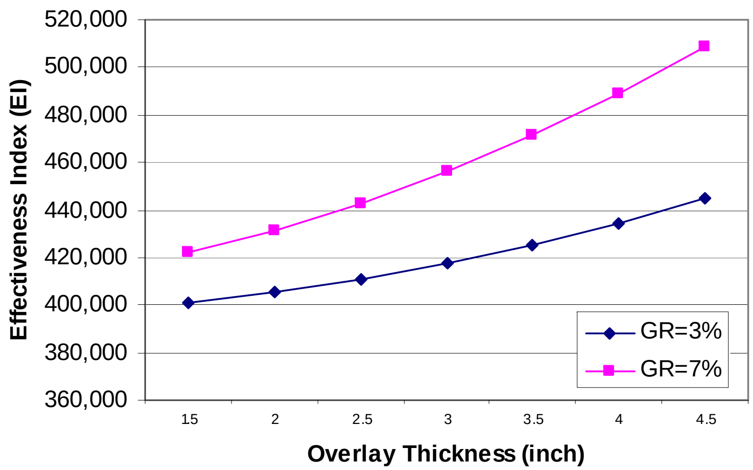


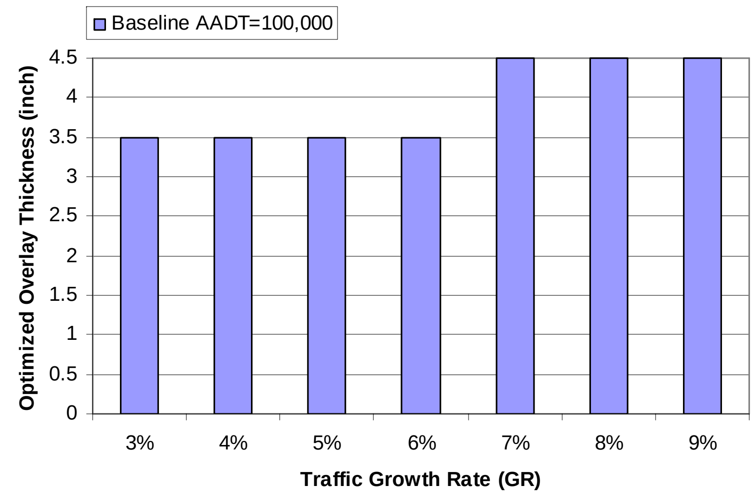


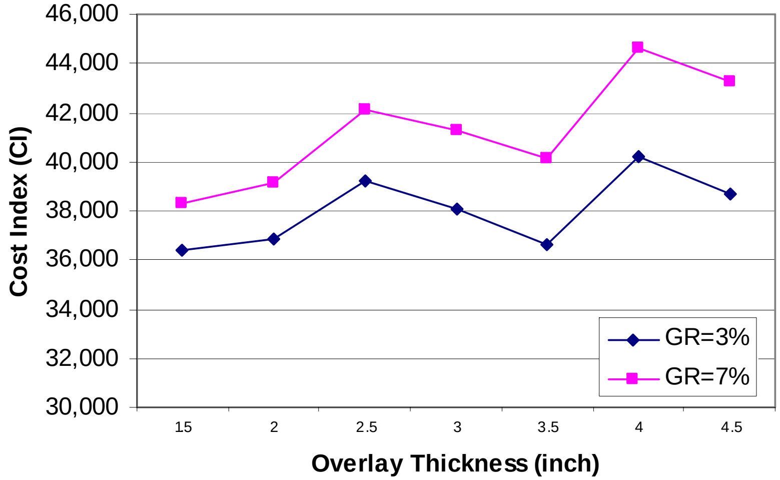


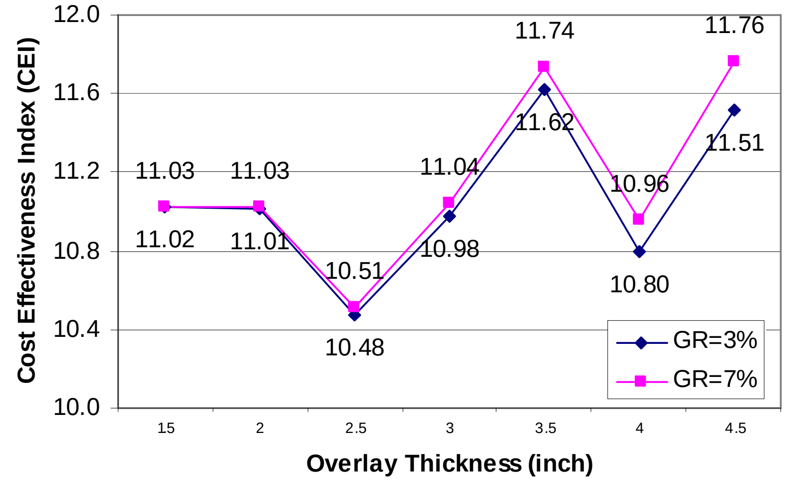
Sensitivity Analysis (Traffic Growth Rate)

- Traffic Growth Rate (GR): 3% - 9%







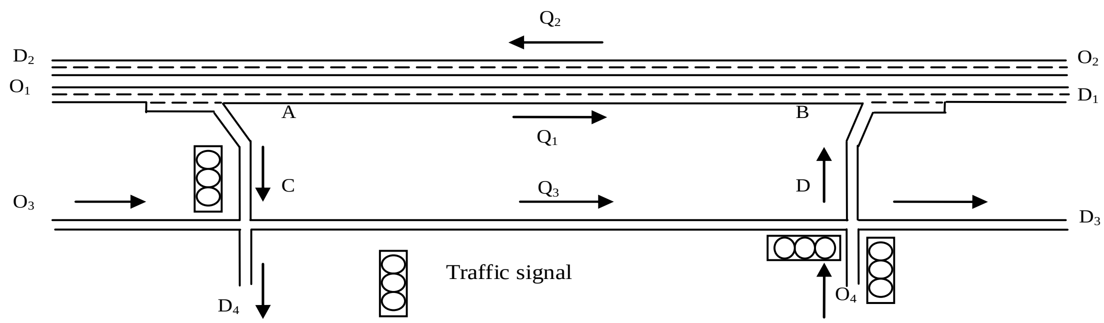


Case Study 2- Findings

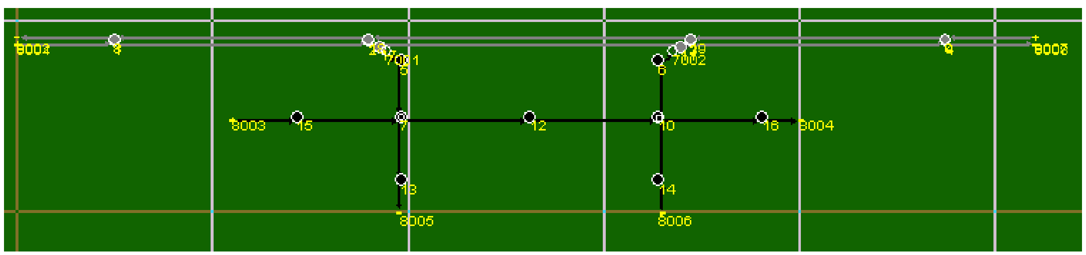
- The extensive experiments demonstrate that the most "desirable" paving strategy may vary, depending on whether long-term user benefit (measured by EI) is taken into account, and whether short-term work zone decisions are optimized.
- High traffic growth rates favor higher intensity strategies
- High interest rates favor the lower intensity strategies

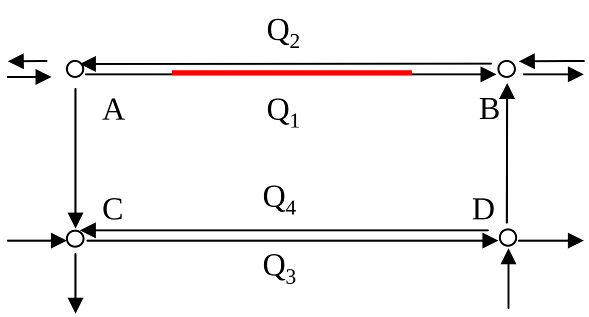
Case Study 3

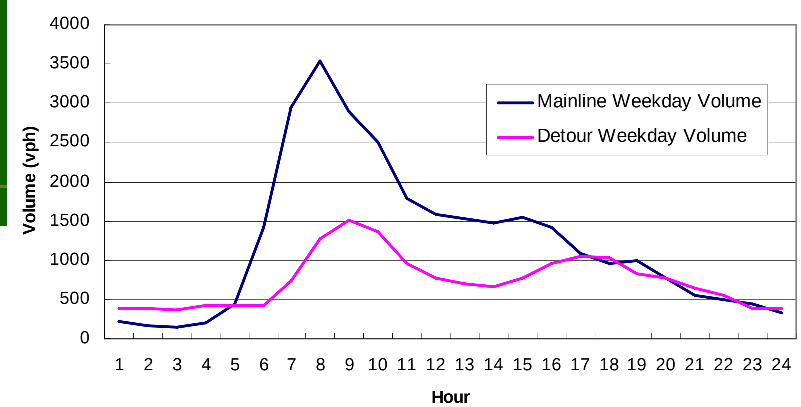
- Test Network



Link	Length	# of Lanes	Capacity	Free Flow Speed
	(mile)	(#)	(vphpl)	(mph)
AB	3.11	2	2,200	65
AC	0.93	1	1,600	45
CD	2.49	1	1,600	45
DB	0.93	1	1,600	45







Mainline AADT =29,446

Detour AADT =17,800

Critical Inputs

- Cyclic Period: Typical Weekday (16:00 pm – 16:00 pm next day)
- Candidate Strategies

Work Rate	z_1 ($/zone)	z_2 ($/lane.mile)	z_3 (hr/zone)	z_4 (hr/lane.mile)
Rate A	1,000	32,000	2	12
Rate B (baseline)	1,000	33,000	2	10
Rate C	1,000	34,000	2	8

- Hybrid Method

Stage	PBSA Algorithm Parameter	S-2PBSA	H-2PBSA
1	Solution Evaluation Method	Simulation	Analytical Model
	# of Generations	11	11
	Population Size	10	10
	Simulation Replication	5	N/A
2	Solution Evaluation Method	Simulation	Simulation
	# of Generations	11	11
	Population Size	2	2
	Simulation Replication	5	5

- Parallel Computing

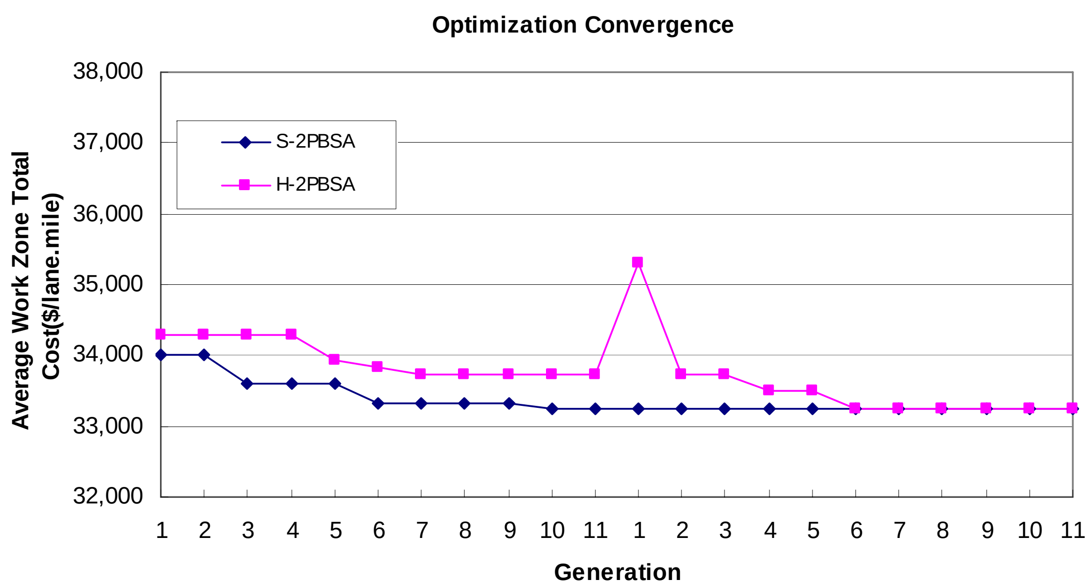
4 PCs with 0.99 GB of RAM and Pentium ® IV3.60 GHz CPU

Optimized Results

- Optimized Results

Optimized Results	S-2PBSA	H-2PBSA
Time Window	16:00-5:00	(16:00-5:00)
Work Duration	13 hours	13 hours
Work Zone Length	0.9 miles	0.9 miles
# of Closed Lane	1	1
Work Rate	Rate A	Rate A
# of Periods Needed	7	7
Agency Cost ($/lane.mile)	33,090	33,090
User Delay Cost ($/lane.mile)	147	147
Total Cost ($/lane.mile)	33,238	33,238

- Convergence



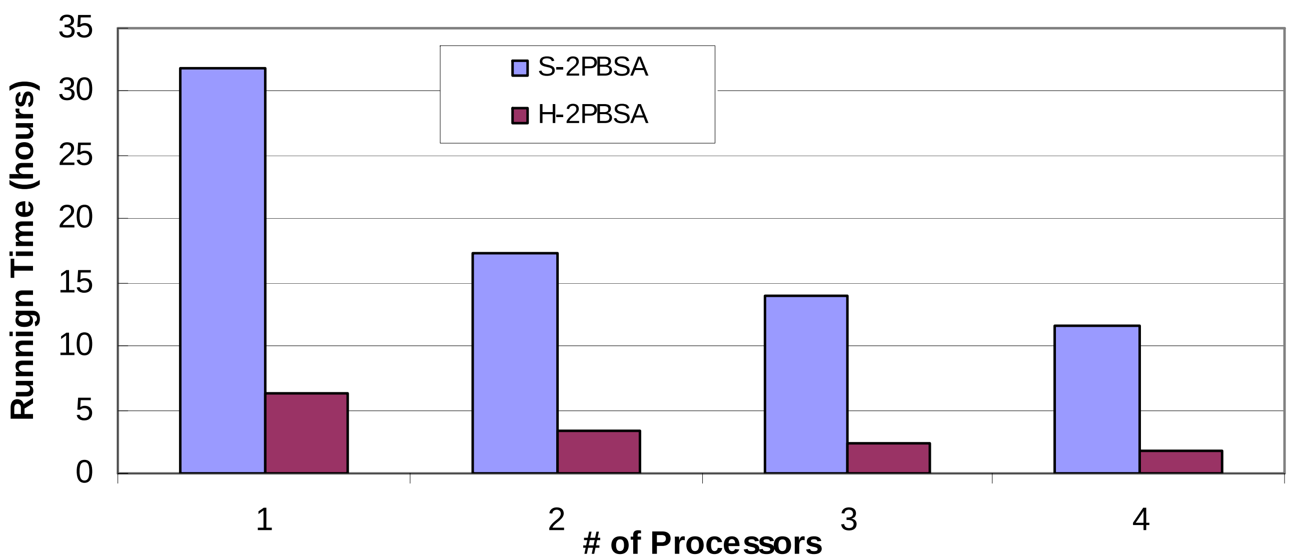
Optimized Results

- Compared with Current Policies

Optimized Results	S-2PBSA	Current Policy 1	Current Policy 2
Time Window	16:00-5:00	9:00-15:00	17:00-5:00
Work Duration	13 hours	6 hours	12 hours
Work Zone Length	0.9 miles	0.33 mile	0.83 mile
# of Closed Lane	1	1	1
Work Rate	Rate A	Rate B	Rate B
# of Periods Needed	7	15	7
Agency Cost ($/lane.mile)	33,090	35,500	34,000
User Delay Cost ($/lane.mile)	147	208,817	98
Total Cost ($/lane.mile)	33,238	244,371	34,098

Running Time

Running Time	S-2PBSA	H-2PBSA
1 Processor	31.8 hours	6.3 hours
2 Processors	17.4 hours	3.4 hours
3 Processors	14.0 hours	2.5 hours
4 Processors	11.6 hours	1.9 hours



Case Study 3- Findings

- The simulation-based work zone decision optimization without using any speed-up methods is quite time-consuming, even for a relatively small problem.
- The hybrid method combines the advantages of the analytical method (quickness) and simulation (more precision). It can yield satisfactory solutions, which are close to simulation-based optimization results, but obtained with much less computation time.
- Experimentation demonstrates the effectiveness of the parallel computing techniques.

6. Contributions

- Improving the analytical model to estimate short-term work zone impacts.
- Introducing traffic impact mitigation strategies into optimization model
- Developing the optimization model for recurrent work zones
- Developing an efficient algorithm to solve the optimization problem
- Developing a simulation-based optimization model
- Jointly optimizing short-term and long-term decisions

7. Future Studies

- Estimate safety-related work zone impacts
- Further improve simulation models
- Improve simulation-based optimization algorithm
- Improve traffic control analysis
- Improve user interface
- Multi-disciplinary optimization for agencies and contractors under different contracting methods
- Uncertainties in input parameters

Thank You!
Q & A