Pavement Resurfacing Intervals in Work Zone Optimization

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ABSTRACT

Lane closures for highway resurfacing involve some intricate tradeoffs between the maintenance cost to highway agencies and the costs of delays and disruptions to motorists. Careful optimization of work zone configuration and dimensions, work schedules and traffic management plans can significantly reduce the overall costs. In addition to previously considered factors, this paper shows how the durability of the pavement and the resulting resurfacing intervals can be considered in optimizing resurfacing plans.

Here we develop a work zone optimization model for multiple-lane highways with time-dependent inflows, a detour, access lanes, and time constraints as well as considering resurfacing intervals and preferred pavement thickness. The algorithm SAUASD (Simulated Annealing for Uniform Alternatives with a Single Detour) is used to find the best schedules for successive work zones. The objective is to minimize total cost, including agency cost and user cost. In our numerical examples with uniform alternatives in successive zones, thinner pavements are preferred at higher interest rates and thicker pavements are preferred at higher traffic volumes. For different priorities regarding total cost, agency cost, or user cost at different traffic levels, various resurfacing interval alternatives are recommended based on our numerical analysis.

INTRODUCTION

Highway resurfacing on multiple-lane two-way highways typically requires closing two or more lanes to set up a work zone. The tradeoffs among various agency and user costs associated with zone configurations and dimensions, work schedules and traffic diversion rates must then be carefully optimized.

Chen and Schonfeld (1) have a developed work zone optimization model for multiple-lane two-way highways with an alternate route and time constraints. The total costs in this previous study only include agency cost and user cost for a one-time resurfacing project. However, it is important highway agencies evaluate the over-all-long-term economic efficiency effectiveness of resurfacing activities. Life-Cycle Cost Analysis (LCCA) is desirable for evaluating new construction or rehabilitation of road pavements. The pavement life cycle cost includes initial cost, future cost, and user delay cost of different pavement alternatives (2). LCCA is an economic analysis approach for comparing the value of alternative pavement types and policies. FHWA (3) developed life-cycle cost analysis for comparing alternative pavement designs. Such cost analyses are developed based on the serviceability concept, which is defined by the pavement condition index (PCI) or pavement serviceability index (PSI) from AASHTO (4).

Figure 1 shows a pavement condition curve and pavement life cycle. A resurfacing interval is defined here to be the period between resurfacing projects, which depends on how long the resurfaced pavement lasts with adequate serviceability. The entire pavement life cycle may include several resurfacing intervals. A longer resurfacing interval reduces the frequency of resurfacing activities and their costs to highway agencies and users; however, it may require a more expensive (e.g., thicker) pavement as well a longer-lasting lane closures whenever the resurfacing is performed. More resurfacing frequencies may not effectively increase the service life cycle of a pavement, but still reduce user cost (3, 5) by improving pavement performance and reducing users' vehicle operating cost.

Previous studies on work zone optimization mostly considered one-time resurfacing cost and user cost without analyzing long-term costs, while LCCA studies focused on pavement types and cost analysis without considering work zone scheduling and its optimization. Rather than optimize only a one-time project costs, it seems considerably more useful to optimize total costs per year over an indefinite series of resurfacing cycles whose resurfacing interval is optimized. This paper extends our previous study (1) on work zone optimization by introducing a quality

dimension, i.e. pavement durability. Thus, it analyzes resurfacing intervals and preferred pavement thickness in optimizing costs per year rather than per resurfacing project. It presents multiple-lane highway models with time constraints for optimizing work plans, including zone lengths, work durations, starting times, pausing times (if any), and diverted fractions. These variables are optimized jointly in this work, by minimizing total cost, including agency cost (resurfacing cost and idling cost) and user cost (user delay cost and accident cost), while dealing with traffic variations over time.

METHODOLOGY AND ASSUMPTIONS

The basic approach followed here is to formulate a comprehensive total cost objective function for multiple-lane highway work zones, and use it to optimize various controllable aspects of work zones. Time constraints are satisfied through penalties on solutions violating those constraints. The SAUASD (Simulated Annealing for Uniform Alternatives with a Single Detour) developed in our previous studies (7, 8) is applied to find the best alternatives along a resurfacing project. Thus, work and traffic management plans that satisfy time constraints are developed for a multiple-lane highway resurfacing project.

The models developed by Chen and Schonfeld (1, 6) and Chen (8) are generally suitable for multiple-lane highways with four, six, or eight lanes. The numerical results presented below are limited to six-lane highways and derived from Chen (1). To resurface all three lanes in one direction of a six-lane highway, while always keeping one of two closed lanes for access, we can assume without loss of generality the following three steps, as shown in Figure 2.

(1) Close Lanes 2 and 3 and resurface Lane 3. Use Lane 2 for access.
(2) Resurface Lane 2. Use Lane 3 for access.
(3) Open Lane 3 and close Lane 1. Resurface Lane 1. Use Lane 2 for access.

The geometry and flows of an analyzed work zone on a six-lane highway is illustrated in Figure 3, where p is the fraction of traffic diverted from the main road to the detour.

Several simplifying assumptions are made in formulating this problem:

1. The flow relations do not depend on which of three lanes in one direction is open for traffic through work zone i.
2. The cost of resurfacing zone i of length L_i is a linear function of the form $C_{mi}=z_1+\alpha n_m f_2 z_2 L_i$, in which z_1 is the fixed cost for setting up a work zone; z_2 is the average additional resurfacing cost per work zone kilometer; n_m is the number of lanes in one direction (default n_m is 3 here for six-lane highways). An average cost

adjustment factor α (e.g. α =0.9) can represent the reduced cost of resurfacing two lanes together in one closure. f_2 is a cost parameter of pavement thickness.

3. The time required to resurface a zone i of length L_i is a linear function of the form $D_i=z_3+\beta n_m f_4 z_4 L_i$, in which z_3 is the setup time for a work zone; z_4 is the additional time required per work zone kilometer, and β is an average time adjustment factor applicable when two lanes are resurfaced together in one closure. f_4 is a duration parameter of pavement thickness.

It should be noted that the resurfacing cost and time functions in Assumptions 2 and 3 vary with pavement thickness t_p as shown in below in the section *Pavement Thickness Parameters*. In this model the pavement thickness t_p is used as a single-variable measure of pavement durability which determines the resurfacing interval in years n, as shown in Table 4, regardless of AADT. A more realistic model where t_p depends on traffic as well as resurfacing interval would be desirable in a future model.

MODEL FORMULATION

Chen and Schonfeld (1) developed a work zone cost function for multiple-lane two-way highways with time-dependent traffic inflows in both directions, as well as with an alternate route and time constraints. Here we extend our previous study and consider resurfacing cycle length and preferred pavement thickness.

The total cost of resurfacing road length L_T by scheduling m work zones, C_T, is (1):

$$\begin{aligned} C_T &= \sum_i^m C_{ti} \\ &= \sum_i^m C_{mi} + \sum_i^m C_{qi} + \sum_i^m C_{vi} + \sum_i^m v_d \Delta t_i + \sum_i^m \frac{(C_{qi} + C_{vi})}{v} \frac{n_a v_a}{10^8} + \sum_i^m C_{pi} \end{aligned} \quad (1)$$

subject to

$t_{s,i-1} \le T_s, T_e \le t_{s,i}$

where C_{mi} is the resurfacing cost for work zone i; C_{qi} is combined queuing delay cost along work zone i and its detour; C_{vi} is combined moving delay cost for the resurfaced road AB and its detour for zone i; $v_d \Delta t_i$ is idling (i.e. a pause in resurfacing) cost per zone; $C_{ai} = \frac{(C_{qi} + C_{vi})}{v} \frac{n_a v_a}{10^8}$ is accident cost per zone; C_{pi} is time constraint penalty cost per zone, T_s and T_e are the starting

and ending of time constraints, respectively; $t_{s,i}$ is starting time for zone *i*. Detailed cost function formulations are provided in Chen and Schonfeld (1).

PAVEMENT THICKNESS PARAMETERS

f_2 and f_4 are cost and duration functions of pavement thickness, respectively. Here we assume that f_2 and f_4 are the following linear functions of pavement thickness, t_p:

$$f_2 = k_1 + k_2 t_p \quad (2)$$

$$f_4 = k_3 + k_4 t_p \quad (3)$$

where k_1 and k_2 are constant parameters for f_2; k_3 and k_4 are constant parameters for f_4. k_1, k_2, k_3, and k_4 are derived from the cost and duration data obtained from the Maryland State Highway Administration. We estimate

$$f_2 = 0.4 + 0.1575 t_p \text{ (SI Unit)} \quad (4)$$

$$f_4 = 0.1 + 0.2362 t_p \text{ (SI Unit)} \quad (5)$$

Hence, the cost and duration of resurfacing zone *i* are as follows

$$C_{mi} = z_1 + \alpha n_m (0.4 + 0.1575 t_p) z_2 L_i \quad (6)$$

$$D_i = z_3 + \beta n_m (0.1 + 0.2362 t_p) z_4 L_i \quad (7)$$

Note that the default values for z_2 and z_4 are based on a pavement thickness of 3.81 cm (1.5 inches). When t_p is 3.81 cm, f_2 and f_4 become 1 (their default value).

OPTIMIZATION

Previous studies by Chen and Schonfeld (7) and Chen (8) show that their Simulated Annealing algorithms, including SAUASD and SAMASD, can reliably find solutions that are very close to the global optimum. Simulated annealing (SA) is a stochastic computational technique derived from statistical mechanics and its search process attempts to avoid becoming trapped in local optima by using a stochastic computational technique to find globally or near globally optimal solutions to large optimization problems. The SAUASD algorithm seeks the best uniform alternative (i.e. same alternative, with similar lane closures, diversion fractions, etc. in each successive zone) for an entire resurfacing project, while SAMASD allows different alternatives

to be optimized for successive zones within a project. Alternatives may differ in lane closure configurations and various other aspects, but in the results presented in this paper they differ only in diversion fractions. The SAUASD algorithm is used in this study. Details of the SAUASD algorithm are provided in Chen and Schonfeld (7) and Chen (8).

ANNUAL RESURFACING COSTS

The total costs for one time resurfacing project, $C_{Present}$, are converted into annual resurfacing costs, C_{Annual}, by using the capital recovery factor. The annual resurfacing cost is equivalent to:

$$C_{Annual} = C_{Present}(A/P, i\%, n) \tag{8}$$

The capital recovery factor $(A/P, i\%, n)$ which converts an initial cost into a uniform series of annual costs in years *1* through *n*, is:

$$(A/P, i\%, n) = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{9}$$

RESULTS

The effects of various parameters on work zone optimization for six-lane highways are examined in this section. Optimized solutions for a 5-km resurfacing project are developed and explained using a numerical example, whose baseline numerical values are shown in Table 1. Baseline values for costs and work durations shown in Table 1 are based on data or estimates provided by the Maryland State Highway Administration. Table 2 shows the traffic distributions over each day on the main road and detour. The annual average daily traffic (AADT) volumes on the main road and detour are 45,000 and 10,000 vehicles, respectively. The peak hours on the main road are 7AM-9AM and 3PM-5PM.

The following discussion is based on our assumed site characteristics, functions relating resurfacing thickness t_p, resurfacing cost C_{mi}, work duration D_i, and resurfacing interval *n* (which are subject to future refinement) and the range of variables analyzed here.

Figure 4 shows the minimized total costs and pavement thickness under different interest rates, *i*: 4%, 5%, 6%, 7%, and 8%. The project is started at 9AM. The results are obtained with SAUASD; thus all zones have the same configuration and diverted fraction, 0.3, which are the optimized results in our previous study (1) which used the same baseline case study. In Figure 4,

the solutions with lower *i* always have the lowest minimized total costs. As expected, higher *i* increases the minimized total cost. Thus, the cost curve for *i*=8% is the highest. Also higher *i* forces thinner pavement: at *i*=4%, the lowest total minimized cost is $12,845/lane.km.year at 7.62 cm (3 inches); at 5% and 6%, the lowest total minimized costs are $13,284 and $13,712/lane.km.year at 6.35 cm (2.5 inches); at 7% and 8%, the lowest total minimized costs are $14,095 and $14,474/lane.km.year at 5.08 cm (2 inches). Table 3 shows the optimized results for thicknesses of 3.81 cm and 7.62 cm at *i*=4%. Although the minimized total cost per lane kilometer of 3.81 cm thickness is lower than for 7.62 cm, $48,113/lane-km for 3.81 cm and $77,094/lane-km for 7.62 cm, the annual minimized total cost for7.62 cm ($12,845/lane.km.year) is lower than for 3.81 cm ($13,255/lane.km.year).

Table 4 shows minimized total costs for different combinations of AADT, pavement thickness, and interest rate. The shadow cells show the lowest minimized total costs and pavement thickness for different interest rates *i*. The results in Table 4 can also be displayed as shown in Figures 5(a) through (e). Figures 5(a) and 5(c) show that 7.62cm is preferable for *i*=4% and 6.35cm for *i*=6% at various levels of traffic. In Figure 5 (b), for *i*=5%, the threshold with respect to AADT occurs near 70,000 vehicles, beyond which t_p=7.62cm becomes preferable to t_p=6.35cm. In Figures 5(d) and 5(e) for *i*=7% and 8%, the thresholds with respect to AADT occur between 65,000 and 70,000 vehicles, beyond which t_p=6.35cm becomes preferable to t_p=5.08cm.

Although thinner pavement is preferable at higher interest rates, the thresholds in Figures 5(b), 5(d) and 5(e) show the trend that at higher interest rates thicker pavement is still preferable for heavy traffic, i.e. 70,000 vehicles, because thicker pavement and a longer resurfacing cycle can reduce annual total cost. Figure 6 shows agency costs and user costs separately and with different scales for different traffic levels at *i*=8%. It also illustrates the effect of converting present total costs by capital recovery factor to annual total costs. Figure 6(a) indicates that annual agency cost for 2.54 cm has the highest curve. In fact, 2.54 cm yields the lowest initial agency cost because thinner pavement thickness is cheaper; however, after converting to annual cost, 5.08 cm yields the lowest annual agency cost for most traffic levels. Beyond AADT=70,000, 3.81 cm yields the lowest annual agency cost. Figure 6(b) shows that there is no significant difference for annual user costs when AADT is low, i.e. 50,000 vehicles/day or lower. When AADT increases, 2.54 cm yields the highest increase and 7.62 cm yields the lowest increase in user costs.

Note that Figure 6 shows that for AADT =70,000 vehicles t_p=3.81 cm yields the lowest agency cost and t_p=7.62 cm yields the lowest user cost; however, Table 4 or Figure 5(e) shows that t_p=6.35 cm has the lowest minimized total cost. Such tradeoffs between agency costs and user costs should be carefully considered in project scheduling to minimize resurfacing cycle costs based on various priorities.

CONCLUSIONS

A work zone planning model for multiple-lane highway resurfacing projects with time-dependent traffic, an alternate route, time constraints, and access lanes, which also considers resurfacing intervals and preferred pavement thickness, is developed to optimize zone lengths, zone starting and ending times, and pauses between zones (if any). It minimizes total costs, including agency cost and user costs.

In our numerical examples with uniform alternatives, thinner pavements are preferred at higher interest rates. Minimized total costs for different combinations of AADT, pavement thickness, and interest rate are presented. When the interest rate is fixed, thicker pavements are preferred at high traffic volumes (main road AADT >65,000 vehicles). For different priorities of total cost, agency cost, or user cost at different traffic levels, various resurfacing interval alternatives are recommended based on our numerical analysis.

Future developments might consider other factors related to life-cycle cost analysis, such as pavement performance and its related costs under various traffic levels, as well as different highway types and lane closure configurations for work zone optimization.

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TABLE 1 Notation and Baseline Inputs for Numerical Example

Variables	Description	Baseline Input Values
$AADT_m$	Annual average daily traffic on main Road	4,5000
$AADT_d$	Annual average daily traffic on detour	8,000
c_o	Maximum discharge rate without work zone	4,800vph
c_w	Maximum discharge rate along work zone	1,200vph
c_{d3}	Maximum discharge rate along detour L_{d2}	1,300vph
f_2	Cost function of Pavement Thickness	-
f_4	Duration function of Pavement Thickness	-
i	Interest Rate	(%)
L_i	Zone length for zone i	- (km)
L_T	Project road length	5 km
L_{d1}	Length of first detour segment	0.5 km
L_{d2}	Length of second detour segment	5 km
L_{d3}	Length of third detour segment	0.5 km
N_{int}	Number of intersections along detour	3
n	Resurfacing Interval	(years)
n_a	Number of accidents per 100 million vehicle hours	40 acc/100mvh [9]
n_m	Number of lanes	3
Q_1^{ij}	Traffic flows in Direction 1 during period j for zone i	-
Q_2^{ij}	Traffic flows in Direction 2 during period j for zone i	-
t_{int}	Average waiting time per intersection	30 sec
$t_{e,i}$	Ending time for zone i	-
$t_{s,i}$	Starting time for zone i	-
t_p	Pavement Thickness	(cm)
Δt_i	Idling time before zone i	-
V	Average work zone speed	50 km/hr
V_f	Free Flow Speed	80 km/hr
v	Value of user time	12 $/veh·hr
v_a	Average accident cost	142,000 $/accident [10]
v_d	Average Cost of Idling Time	800 $/hr
z_1	Fixed setup cost	1,000 $/zone
z_2	Average resurfacing cost per lane·kilometer	50,000 $/lane·km
z_3	Fixed setup time	2 hr/zone
z_4	Average resurfacing time per lane·kilometer	4 hr/lane·km

TABLE 2 AADT and Hourly Traffic Distribution on a Six-Lane Two-Way Highway (Main Road) and a Two-Lane Two-Way Highway (Alternate Route)

Hour	Main Road Volume (Both Directions)	Q_1 (vph)	Q_2 (vph)	Normal Volume on Detour (Both Directions)	Q_3 (vph)	Q_4 (vph)
0	1,048	503	545	180	86	94
1	1,048	503	545	150	72	78
2	1,049	472	577	131	59	72
3	1,049	556	493	130	69	61
4	1,049	556	493	151	80	71
5	1,049	556	493	180	95	85
6	1,656	944	712	251	143	108
7	3,006	1,623	1,383	350	196	154
8	3,456	1,935	1,521	419	234	185
9	2,700	1,512	1,188	500	270	230
10	2,398	1,223	1,175	540	275	265
11	1,949	994	955	559	286	273
12	1,800	900	900	570	285	285
13	1,656	861	795	639	333	306
14	1,949	994	955	680	347	333
15	2,556	1,355	1,201	730	387	343
16	3,298	1,616	1,682	930	456	474
17	2,534	1,191	1,343	699	301	398
18	2,250	1,058	1,192	551	259	292
19	2,106	990	1,116	470	221	249
20	1,800	828	972	380	175	205
21	1,498	719	779	320	154	166
22	1,048	503	545	260	125	135
23	1,048	503	545	230	108	122
AADT	45,000	22,895	22,105	10,000	5,016	4,984

TABLE 3 Optimized Results for Numerical Example, Main Road AADT=45,000

(a) Thickness: 3.81 cm, interest rate: 4%

Zone Number	Optimal Length (km)	Duration (hr)	Starting Time	Ending Time	Idle Time	Total Cost ($/zone)
1	0.77	6.00	9.00	15.00	0.00	111,169
2	2.30	13.97	17.02	6.99	2.02	330,123
3	0.77	6.00	9.00	15.00	2.01	112,777
4	1.16	8.03	17.03	1.06	2.03	167,630
Total	5.00	34.00			6.06	721,698
Resurfacing cost						705,252
Idling cost						4,852
Agency cost						810,104
Queuing delay cost						0
Moving delay cost						11,540
Accident cost						55
User cost						11,595
Total cost per cycle						721,698
Total cost/project-km ($/lane-km)						48,113
Resurfacing Interval (years)						4
(A/P, 4%, 4)						0.27549
Total cost/lane-km-year ($/lane-km-yr)						13,255

(b) Thickness: 7.62 cm, interest rate: 4%

Zone No.	Optimized length (km)	Duration (hr)	Starting time (0-23.99)	Ending time (0~23.99)	Idling time (hr)	Total Cost ($/zone)
1	0.40	6.00	9.00	15.00	0.00	93,857
2	1.21	13.95	17.00	6.96	2.00	277,574
3	0.40	5.91	9.09	15.00	2.14	93,371
4	1.21	13.95	17.00	6.96	2.00	277,574
5	0.40	6.00	9.00	15.00	2.04	95,490
6	1.21	13.95	17.00	6.96	2.00	277,574
7	0.16	3.63	9.00	12.63	2.04	40,975
Total	5.00	63.40			12.23	1156,416
Resurfacing cost						1,129,205
Idling cost						9,786
Agency cost						1,138,991
Queuing delay cost						0
Moving delay cost						17,343
Accident cost						82
User cost						17,425
Total cost per cycle						1,156,416
Total cost/project-km ($/lane-km)						77,094
Resurfacing Interval (years)						7
(A/P, 4%, 7)						0.16661
Total cost/lane-km-year ($/lane-km-yr)						12,845

TABLE 4 Annual Minimized Total Costs v.s. AADT, Thickness and Interest Rate

Pavement Thickness		Interest rate	years	AADT						
				40,000	45,000	50,000	55,000	60,000	65,000	70,000
t_p (inch)	t_p (cm)	i	n	Annual Minimized Total Cost ($/lane.km.year)						
1.0	2.54	4%	3	13,922	13,948	13,991	14,065	14,193	14,408	14,774
1.5	3.81		4	13,230	13,255	13,294	13,357	13,472	13,639	13,952
2.0	5.08		5	12,959	12,982	13,025	13,083	13,171	13,280	13,595
2.5	6.35		6	12,840	12,862	12,900	12,950	13,027	13,154	13,288
3.0	7.62		7	12,822	12,845	12,886	12,934	13,020	13,134	13,219
1.0	2.54	5%	3	14,187	14,214	14,257	14,333	14,463	14,682	15,055
1.5	3.81		4	13,543	13,568	13,609	13,673	13,790	13,961	14,283
2.0	5.08		5	13,325	13,349	13,393	13,453	13,544	13,655	13,980
2.5	6.35		6	13,261	13,284	13,323	13,375	13,455	13,586	13,724
3.0	7.62		7	13,299	13,323	13,366	13,417	13,505	13,623	13,712
1.0	2.54	6%	3	14,454	14,481	14,525	14,602	14,735	14,958	15,338
1.5	3.81		4	13,859	13,885	13,926	13,992	14,112	14,287	14,616
2.0	5.08		5	13,695	13,720	13,765	13,827	13,920	14,035	14,368
2.5	6.35		6	13,689	13,712	13,752	13,805	13,888	14,023	14,166
3.0	7.62		7	13,785	13,810	13,855	13,907	13,998	14,121	14,213
1.0	2.54	7%	3	14,722	14,749	14,794	14,873	15,008	15,236	15,623
1.5	3.81		4	14,178	14,204	14,247	14,314	14,437	14,616	14,952
2.0	5.08		5	14,070	14,095	14,142	14,205	14,301	14,419	14,761
2.5	6.35		6	14,122	14,146	14,187	14,242	14,327	14,467	14,614
3.0	7.62		7	14,279	14,305	14,351	14,405	14,500	14,627	14,722
1.0	2.54	8%	3	14,992	15,020	15,065	15,146	15,283	15,515	15,909
1.5	3.81		4	14,500	14,526	14,570	14,639	14,764	14,947	15,291
2.0	5.08		5	14,449	14,474	14,522	14,587	14,686	14,807	15,159
2.5	6.35		6	14,560	14,585	14,628	14,685	14,773	14,916	15,068
3.0	7.62		7	14,781	14,808	14,856	14,911	15,009	15,141	15,239

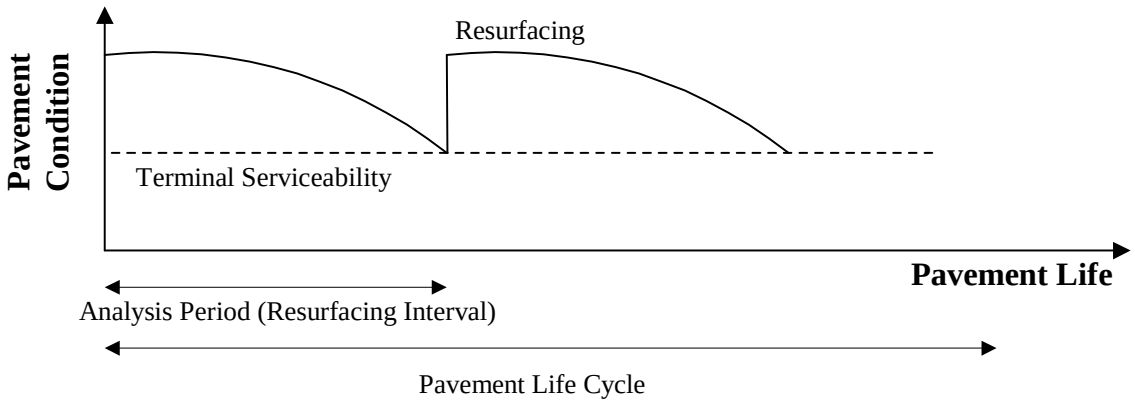


FIGURE 1 Analysis Period for a Pavement Design Alternative (Derived from Reference 3)

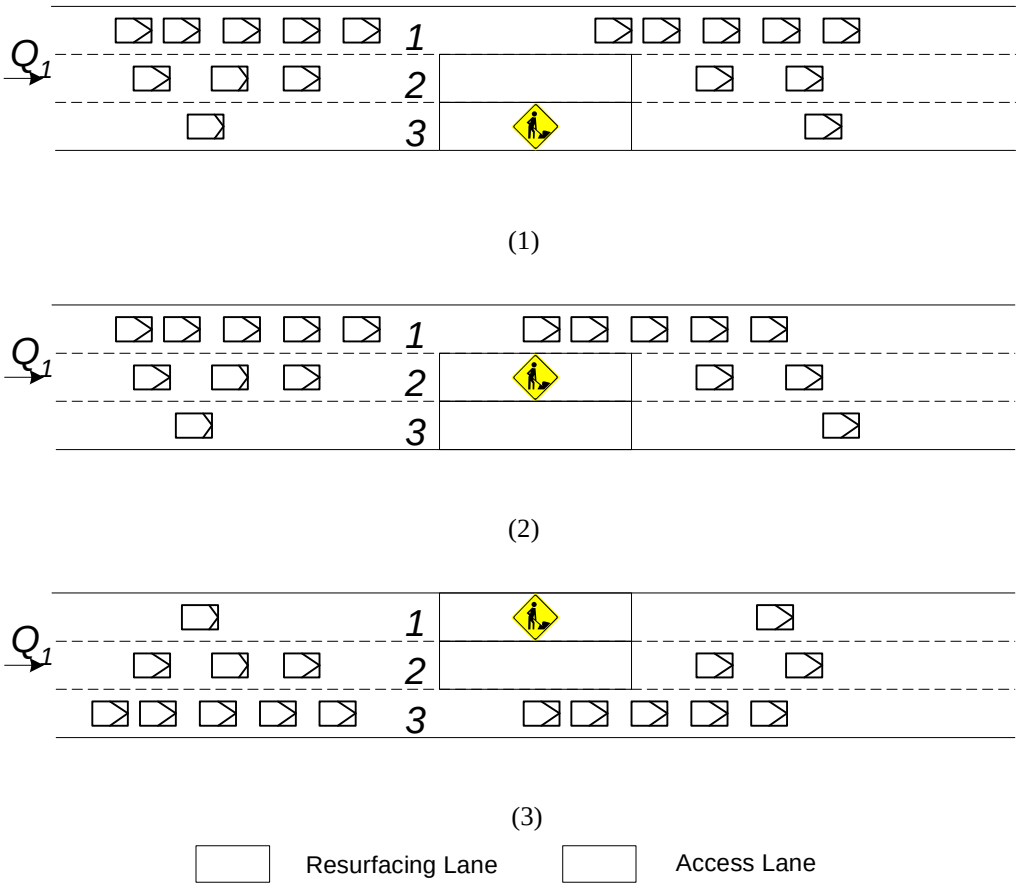


FIGURE 2 Three Steps in Resurfacing Three Lanes on a Six-Lane Highway

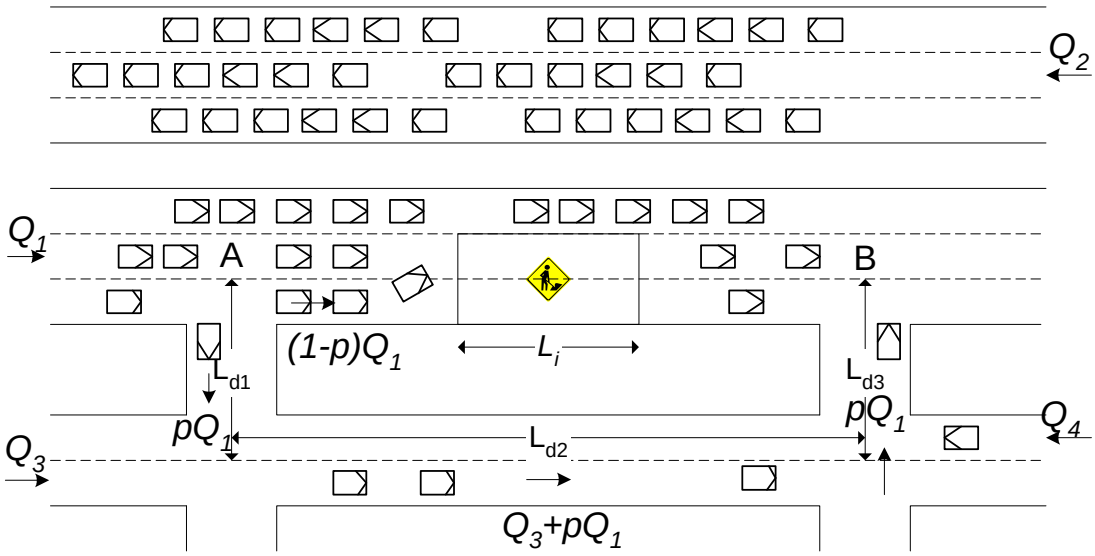


FIGURE 3 Geometry and Flows of Analyzed Work Zone Activities on a Six-Lane Highway

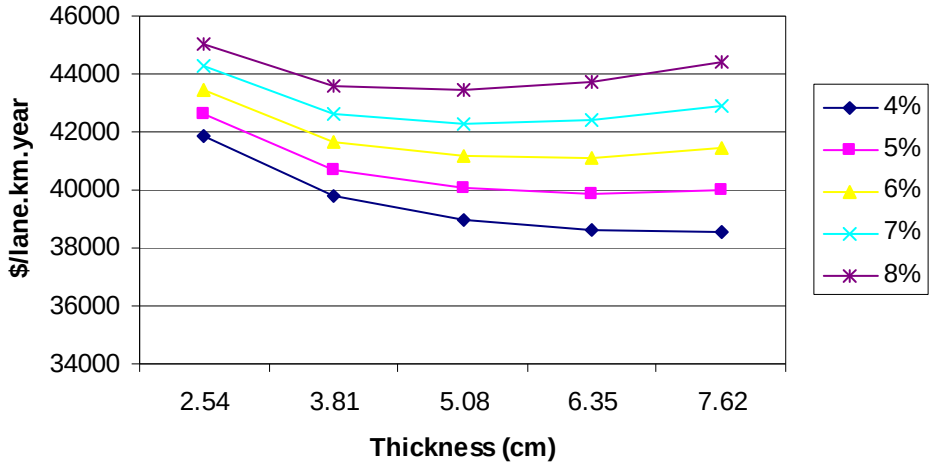
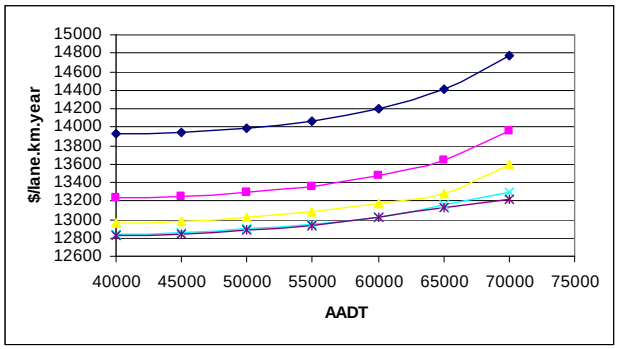
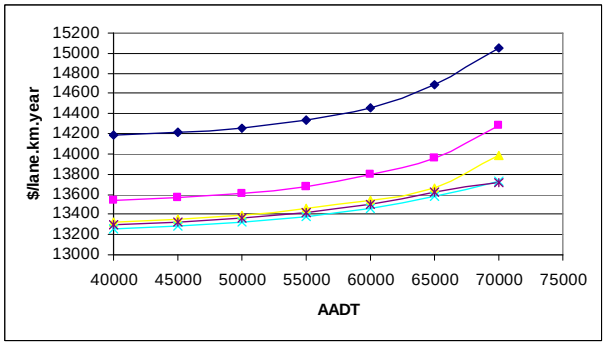


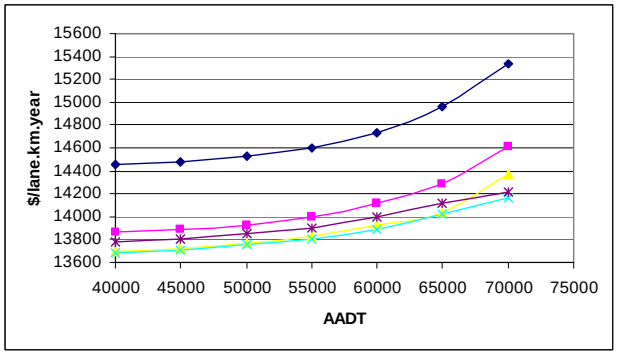
FIGURE 4 Minimized Total Cost vs. Pavement Thickness, AADT=45,000



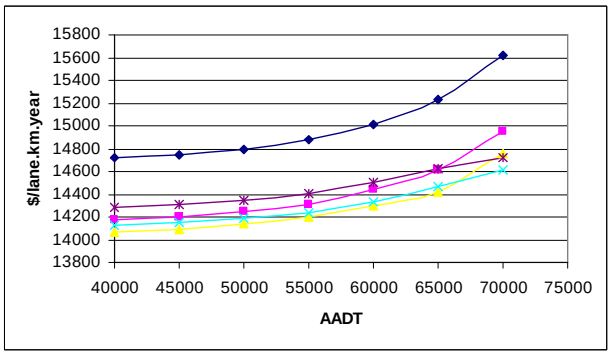
(a)



(b)



(c)



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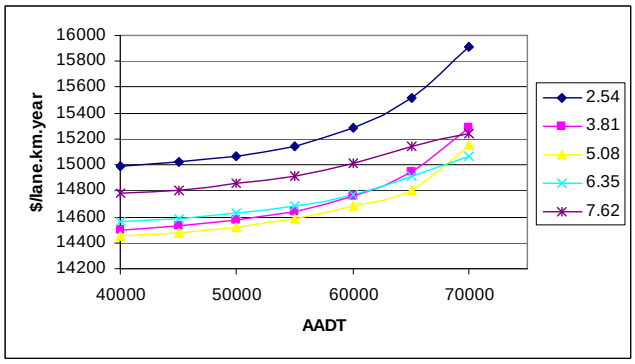
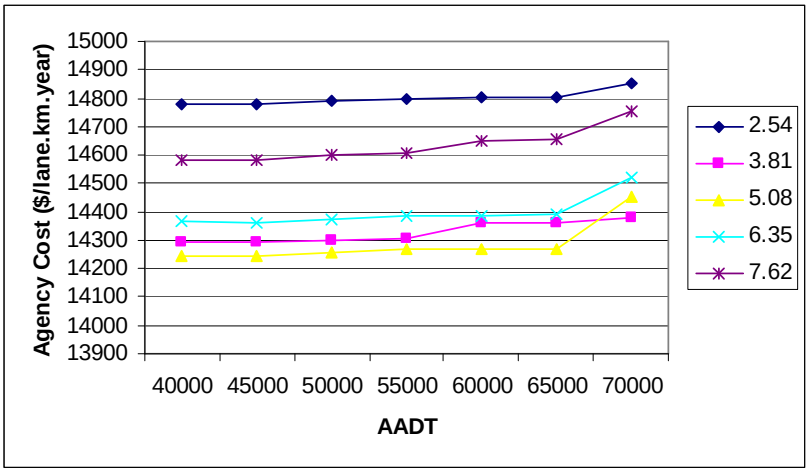


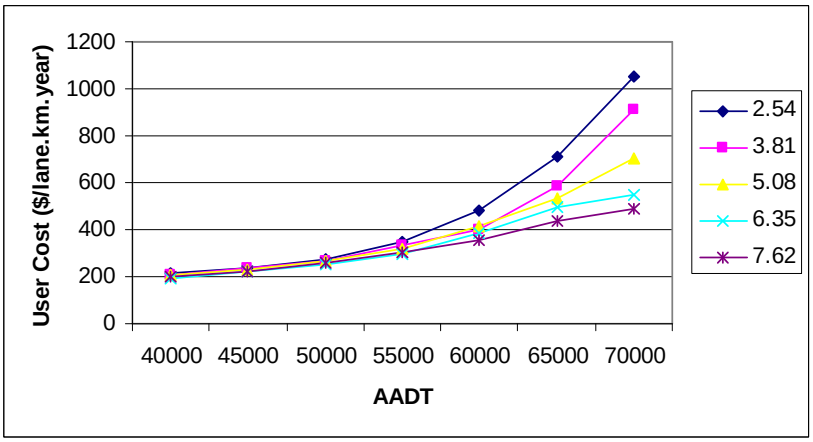
(e)

FIGURE 5 Minimized Total Cost vs. AADT

(a) rate = 4% (b) rate = 5% (c) rate = 6% (d) rate = 7% (e) rate = 8%



(a)



(b)

FIGURE 6 Minimized Total Cost vs. AADT, *i*=8%, (a) Agency Cost (b) User Cost