BRIDGE MANAGEMENT SYSTEM WITH PRACTICAL WORK ZONE PLANNING

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ABSTRACT

Currently North America is facing significant challenges as a result of the deteriorated infrastructure assets and the limited repair funds. A recent study showed that Canada's roads and highway infrastructure networks need $66 Billion over the next 10 years to bring these networks to acceptable service conditions. Among the transportation assets, bridges are considered as vital links due to their direct impact on the circulation of traffic a network and associated user costs. This has created an increasing pressure on Municipalities to develop new techniques for better management of bridge networks. However, developing optimum maintenance and repair programs that are cost effective and have least disruption to users, particularly at the work zones, is a complex task.

This paper presents an innovative optimization model for supporting decisions related to optimum work zone strategies for bridges. The novelty of the proposed model stems from: (1) incorporating suitable traffic control plan for each bridge under repair; (2) considering the user costs associated with traffic control and work zone plans for each bridge; and (3) using a powerful evolutionary algorithm to optimize the selection of the best work zone strategy for each bridge so that the associate user cost is minimized. A description of the proposed model and its implementation are presented in this paper along with an example application to demonstrate its benefits to municipalities and owner organizations.

KEY WORDS

Work zone strategy, traffic control plan, Bridge management systems, user cost, evolutionary algorithm, shuffled frog leaping.

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INTRODUCTION

Currently, the infrastructure in North America has been seriously deteriorating due to aging, insufficient capacity, and limited repair funds. A recent report from the federal, provincial and territorial deputy ministers of transportation - Canada showed that Canada's roads and highways need $66 Billion over the next 10 years to overcome the infrastructure gap between the needs required and the services (Toronto Star 2005). This large need has created pressure on all governmental levels to widely invest on improving the infrastructure assets through proper prioritization of assets as well as selection of the most appropriate repair strategies. Among the transportation assets, bridges are the most critical assets, as construction work zones cause partial or full closure of bridges, thus directly impacting the business sector and the general public as well.

Although work zones provide a means for performing repair and rehabilitation projects without fully closing the bridge, they have several impacts. These impacts include higher user cost, increased accident rates, and user delay (Martinlli and Xu 1996). The later impact is considered the most significant problem associated with work zones. In some cases, bridge repair operations may fail due to complete congestion at the bridge location, especially in peak time periods.

The problem with work zone usually arises from the conflict of interest among highway agencies, roadway users, and contractors (Najafi and Soares 2001). While the contractor and agency objective is to minimize cost, the users' objective is to minimize the delay. Therefore, it is important to investigate the impact of different work zone strategies and to select the optimum one.

Several efforts had been carried out to quantify user costs at work zones during repair and maintenance of pavement projects (Martinlli and Xu 1996; Lee and Ibbs 2005; and Lindly and Clark 2004). However, little efforts have focused on bridges, and the impact of work zone has been overlooked in most of bridge management systems such as Pontis (2001).

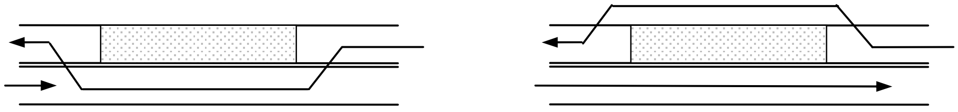
To assist decision makers in the optimum selection of work zone strategies for bridge-deck repairs, this paper presents a comprehensive model to minimize both agencies and users' costs. The model development and its implementation as an optimization problem are outlined and an example is presented to demonstrate its practicality. The output of the model is an optimum work zone strategy for each bridge under repair and rehabilitation.

USER COST AT BRIDGE WORK ZONE

Calculating the user cost at a work zone requires analysis of three components: 1) the traffic control plan; 2) the work zone construction schedule (work zone window); and 3) the traffic flow analysis. These are discussed in the following subsections.

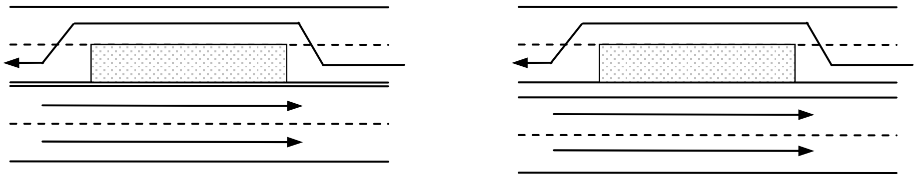
TRAFFIC CONTROL PLAN

The basic concept of a traffic control plan is to permit the contractor to work on a bridge while maintaining safe and uniform flow of traffic. Various types of traffic control plans (TCPs) are available for highway maintenance and are decided based on the number of highway lanes, and the type of repair required. He (1997) suggested the traffic control plans shown in Figure 1 for a variety of highway configurations. Adapting the traffic control plans in Figure 1 to the bridge environment is summarized in Table 1. The costs associated with these TCPs are discussed later. It is noted that the TCP is not a variable in the present model, rather each bridge has a suitable TCP depending on its configuration (from Table1).



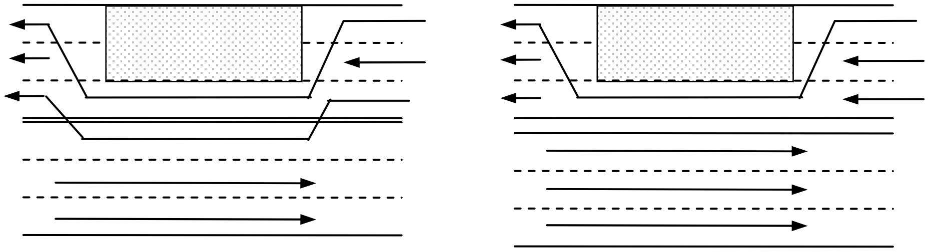
Plan1: Two-Lane Undivided

Plan2: Two-Lane- Shoulder



Plan3: Four-Lane Undivided

Plan5: Four-Lane Divided



Plan4: Six-Lane Undivided

Plan6: Six-Lane Divided

Figure 1: Traffic Control Plans for Different Highway Configurations (He 1997)

WORK ZONE CONSTRUCTION WINDOW

Highway repair and rehabilitation window (time of day to do the work) is traditionally done during nighttime because daytime closures cause unacceptable delays to weekday peak travel. However, the disadvantage of having nighttime closures is that they may lead to lower quality. Also, nighttime closures may result in longer closure time, higher construction and traffic control plans costs, and greater traffic delay to users (Lee and Ibbs 2005). Other construction window strategies for accelerating the construction have been proposed by Lee and Ibbs (2005), such as continuous (round-the-clock) operations either during a 55h weekend or a 72 h weekday closures. As such, the present paper uses four construction window strategies (nighttime shifts, weekend closure, weekday closure, and full closure), or a combination of them, as a variable for each bridge, with associated user costs explained in the next subsection.

Table 1: Suggested Traffic Control Plans for Different Bridge Configurations

Bridge description	TCP	Notes
2-Lane	Plan 1	Only one lane is opened for traffic in two directions
2-Lane-with wide shoulder	Plan 2	Using the shoulder as a lane in the work zone area
4-Lane-divided	Plan 3	One lane closed in one direction
4-Lane-undivided	Plan 5	One lane closed in one direction
6-Lane-divided	Plan 4	Two lanes closed in one direction
6-Lane- undivided	Plan 6	Two lanes closed in one direction and one lane in the other direction
Deck full replacement	Plan 9	Bridge full closure and complete detour

TRAFFIC FLOW ANALYSIS AND COST CALCULATION

Given a TCP and a decided work zone window, a detailed analysis of the user costs is carried out through traffic flow analysis. User costs are divided into three components: Vehicle operating Cost (VOC); User Delay Cost; and Crash Costs. These costs are considered in the following steps of a detailed Traffic Flow Analysis:

Step 1: Hourly Traffic Volume

User costs are directly dependent on the volume and operating characteristics of the traffic on the bridge. The important characteristics of the traffic in a work zone are: 1) the annual average daily traffic (AADT), which is estimated to have a 2% annual traffic increase; and 2) the hourly flow distribution related to the daily AADT. Data related to the AADT and the hourly traffic distribution is often available at the authorities and Municipalities. Table 2 shows an example of hourly traffic distribution for illustration purpose (USDOT/FHWA 1998). The table provides a distribution factor (% AADT) for each hour of the day for different highway types. Based on this factor, the hourly traffic can be calculated as:

$$Hourly\,Traffic = AADT \times DistributionFactor \tag{1}$$

In this paper, Equation 1 and the distribution factors shown in Figure 2 are used to calculate the hourly traffic at different bridge locations, as a function of the highway type linked to the bridge and the AADT associated with that bridge.

Step 2: Free flow and workzone capacity

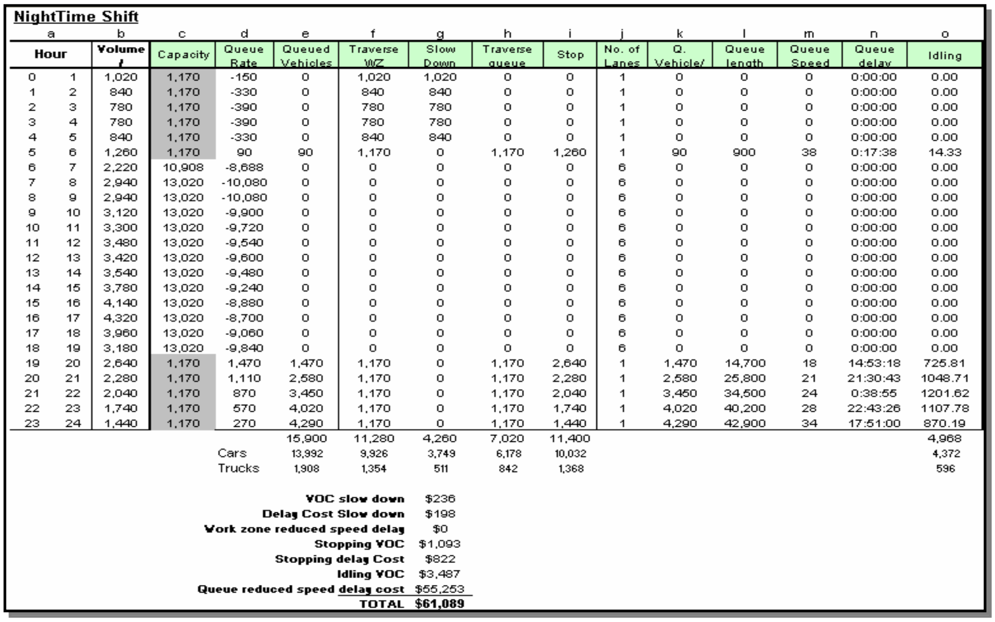
Once the hourly traffic volume is calculated at the bridge location, the user delay at the bridge will depend on the free flow capacity of the highway in the upstream as well as the capacity of the work zone to dissipate the traffic. The maximum free flow capacity of a highway can be determined from the Highway Capacity Manual (HCM 1994): 2,200 passenger cars per hour per lane (pcphpl) for a 2-lanes highway and 2,300 pcphpl for 3 or more lanes. Also, the dissipation rate of the work zone is estimated to be 1,818 pcphpl (USDOT/FHWA 1998).

Table 2: Example of Hourly Traffic Distribution (USDOT/FHWA 1998)

Hour		**Distribution Factor (% of AADT)**		**Hour**		**Distribution Factor (% of AADT)**	
From	**To**	**Interstate**	**Other**	**From**	**To**	**Interstate**	**Other**
0	1	1.7%	0.9%	12	13	5.7%	5.7%
1	2	1.4%	0.5%	13	14	5.9%	5.9%
2	3	1.3%	0.5%	14	15	6.3%	6.6%
3	4	1.3%	0.5%	15	16	6.9%	7.7%
4	5	1.4%	0.9%	16	17	7.2%	8.0%
5	6	2.1%	2.3%	17	18	6.6%	7.4%
6	7	3.7%	4.9%	18	19	5.3%	5.5%
7	8	4.9%	6.2%	19	20	4.4%	4.3%
8	9	4.9%	5.5%	20	21	3.8%	3.6%
9	10	5.2%	5.3%	21	22	3.4%	3.0%
10	11	5.5%	5.4%	22	23	2.9%	2.3%
11	12	5.8%	5.6%	23	24	2.4%	1.5%

Step 3: user cost calaculations at work zones

With the free flow and work zone capacity determined, a detailed analysis on an hourly basis has been conducted on an Excel spreadsheet. Figure 2 shows an example for a bridge with 4 lanes where the TCP is to have only one lane opened for traffic and the decided work zone strategy is nighttime shifts. The shaded areas in column (c) indicate the work zone construction window. Column (d) shows the number of queued vehicles. The user costs at the work zone depends on whether the traffic will experience free flow (i.e. no full stopping at the work zone), or the traffic will experience forced flow.



NightTime Shift

a		b	c	d	e	f	g	h	i	j	k	l	m	n	o
Hour		**Volume /**	Capacity	Queue Rate	Queued Vehicles	Traverse WZ	Slow Down	Traverse queue	Stop	No. of Lanes	Q. Vehicle/	Queue length	Queue Speed	Queue delay	Idling
0	1	1,020	1,170	-150	0	1,020	1,020	0	0	1	0	0	0	0:00:00	0.00
1	2	840	1,170	-330	0	840	840	0	0	1	0	0	0	0:00:00	0.00
2	3	780	1,170	-390	0	780	780	0	0	1	0	0	0	0:00:00	0.00
3	4	780	1,170	-390	0	780	780	0	0	1	0	0	0	0:00:00	0.00
4	5	840	1,170	-330	0	840	840	0	0	1	0	0	0	0:00:00	0.00
5	6	1,260	1,170	90	90	1,170	0	1,170	1,260	1	90	900	38	0:17:38	14.33
6	7	2,220	10,908	-8,688	0	0	0	0	0	6	0	0	0	0:00:00	0.00
7	8	2,940	13,020	-10,080	0	0	0	0	0	6	0	0	0	0:00:00	0.00
8	9	2,940	13,020	-10,080	0	0	0	0	0	6	0	0	0	0:00:00	0.00
9	10	3,120	13,020	-9,900	0	0	0	0	0	6	0	0	0	0:00:00	0.00
10	11	3,300	13,020	-9,720	0	0	0	0	0	6	0	0	0	0:00:00	0.00
11	12	3,480	13,020	-9,540	0	0	0	0	0	6	0	0	0	0:00:00	0.00
12	13	3,420	13,020	-9,600	0	0	0	0	0	6	0	0	0	0:00:00	0.00
13	14	3,540	13,020	-9,480	0	0	0	0	0	6	0	0	0	0:00:00	0.00
14	15	3,780	13,020	-9,240	0	0	0	0	0	6	0	0	0	0:00:00	0.00
15	16	4,140	13,020	-8,880	0	0	0	0	0	6	0	0	0	0:00:00	0.00
16	17	4,320	13,020	-8,700	0	0	0	0	0	6	0	0	0	0:00:00	0.00
17	18	3,960	13,020	-9,060	0	0	0	0	0	6	0	0	0	0:00:00	0.00
18	19	3,180	13,020	-9,840	0	0	0	0	0	6	0	0	0	0:00:00	0.00
19	20	2,640	1,170	1,470	1,470	1,170	0	1,170	2,640	1	1,470	14,700	18	14:53:18	725.81
20	21	2,280	1,170	1,110	2,580	1,170	0	1,170	2,280	1	2,580	25,800	21	21:30:43	1048.71
21	22	2,040	1,170	870	3,450	1,170	0	1,170	2,040	1	3,450	34,500	24	0:38:55	1201.62
22	23	1,740	1,170	570	4,020	1,170	0	1,170	1,740	1	4,020	40,200	28	22:43:26	1107.78
23	24	1,440	1,170	270	4,290	1,170	0	1,170	1,440	1	4,290	42,900	34	17:51:00	870.19
					15,900	11,280	4,260	7,020	11,400						4,968
				Cars	13,992	9,926	3,749	6,178	10,032						4,372
				Trucks	1,908	1,354	511	842	1,368						596

VOC slow down	$236
Delay Cost Slow down	$198
Work zone reduced speed delay	$0
Stopping VOC	$1,093
Stopping delay Cost	$822
Idling VOC	$3,487
Queue reduced speed delay cost	$55,253
TOTAL	**$61,089**

Figure 2: Work Zone User Cost Calculation Sheet

In case of free flow (i.e. cars are not stopping at the work zone), three types of user costs are considered: 1) *speed change delay*; 2) *speed change vehicle operating cost (VOC)*; and 3) *reduced speed* (Lindly and Clark 2004). First, the *speed change delay* is calculated based on the additional time required for the users to decelerate from the upstream speed to the work zone speed. Second, the *speed change VOC* is the vehicle operating cost associated with decelerating from the upstream speed to the work zone speed and then accelerating back to the upstream speed. Third, the *reduced speed delay* is calculated based on the additional time required for the users to traverse the work zone at reduced speed.

In case of forced flow (i.e. the hourly traffic demand exceeds the work zone capacity), a queue is formed in the upstream of the work zone. The forced flow imposes four types of user costs: 1) *stopping delay*; 2) *stopping VOC*; 3) *queue delay*; and 4) *idling VOC*. First, the *stopping delay* is calculated based on: a) the additional time required for the users to come to a complete stop from the upstream; and b) the additional time required to accelerate back to the downstream speed after leaving the work zone. Second, the *stopping VOC* is the vehicle operating cost associated with stopping from the upstream and accelerating back to the downstream speed after leaving the work zone. Third, the *queue delay* is the calculated based on the time required for the users to pass through the queue. Fourth, the *idling VOC* is the vehicle operating cost associated with the stop-and-go driving through the queue. More details on calculating users' costs can be found in Lindly and Clark (2004), and USDOT/FHWA (1998).

For the example of the nighttime construction window in Figure 2, the summation of the seven user costs are shown at the bottom of the figure, indicating the impact of the TCP and the work zone strategy on the user cost. Given that a bridge can have a different work zone strategy in each day of repair (during the construction window), then, the total user cost for a bridge (i) is the summation of user costs for each work zone strategy (*j*) multiplied by the number of days of applying that strategy, as given in Equation 2.

$$UserCost_i = \sum_{j=1}^{4} (DailyUserCost_j \times Days_j) \qquad (2)$$

Where, j = work zone strategy (1=nighttime; 2=weekend shifts; 3=weekday closure; and 4=full closure); and $Days_j$ = the number of days for applying work zone strategy j.

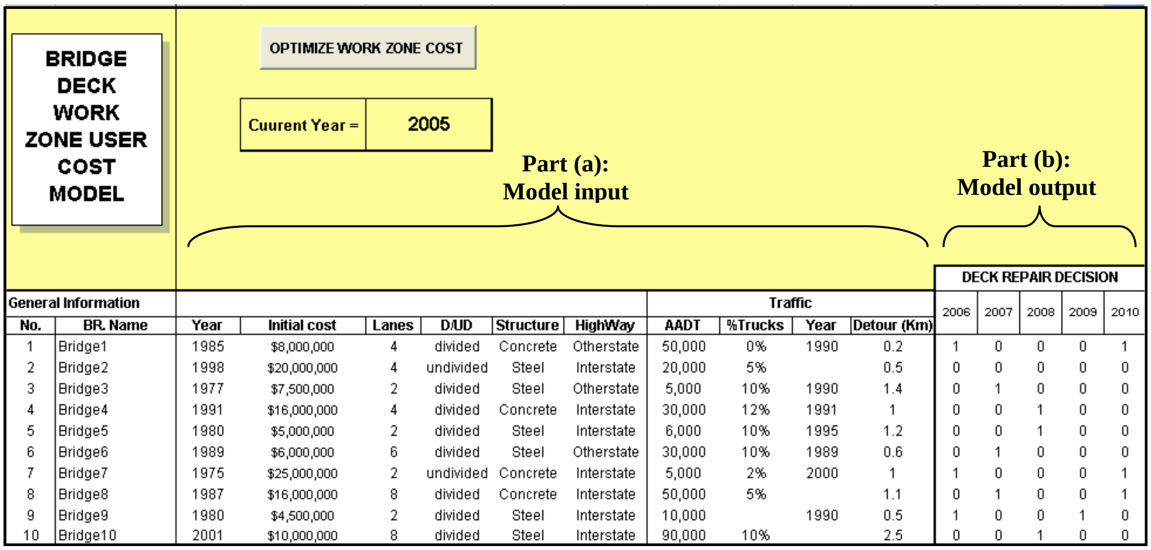
BRIDGE DECK MANAGEMENT SYSTEM IMPLEMENETATION

Having defined the user cost calculation procedure, a basic bridge deck management system (BDMS) has been extended to incorporate these calculations into its decision support process. The implementation of the BDMS is defined in the following subsections.

BASIC BRIDGE DECK MANAGEMENT SYSTEM

A basic Bridge Deck Management System (BDMS) was developed by Hegazy et. al (2004) as a spreadsheet system that supports both network level and project level decisions, without suggesting a work zone strategy. It uses the FHWA condition rating for assessing the deck condition, ranging from 9-best condition to 3-critical condition. The basic BDMS also incorporates a Markov deterioration model to describe the deterioration behavior for the deck with time. Three repair options are used for bridge decks and the cost of repair is estimated as a percentage of initial cost: 1 = light repair; 2 = medium repair; and 3 = extensive repair. Light repairs are intended to restore the deck surface and include patching, sealing, and cleaning of debris. Medium repair, on the other hand, involve strengthening or increasing bridge deck thickness. Also, the extensive repair or deck replacement mandates complete or partial replacement of the deck, often leading to complete closure for traffic.

Figure 3 illustrates the main components of the basic BDMS model: part (a) inputs, including the bridge year of construction, initial cost, number of lanes, structure type, highway type, and other information related to the traffic; and Part (b) outputs, showing the optimum repair types for each bridge and its year of application (e.g., bridge 1 requires a repair of type 1 in year 2006 and another type 1 repair in year 2010).



Cuurent Year = 2005

General Information								Traffic				DECK REPAIR DECISION				
No.	BR. Name	Year	Initial cost	Lanes	D/UD	Structure	HighWay	AADT	%Trucks	Year	Detour (Km)	2006	2007	2008	2009	2010
1	Bridge1	1985	$8,000,000	4	divided	Concrete	Otherstate	50,000	0%	1990	0.2	1	0	0	0	1
2	Bridge2	1998	$20,000,000	4	undivided	Steel	Interstate	20,000	5%		0.5	0	0	0	0	0
3	Bridge3	1977	$7,500,000	2	divided	Steel	Otherstate	5,000	10%	1990	1.4	0	1	0	0	0
4	Bridge4	1991	$16,000,000	4	divided	Concrete	Interstate	30,000	12%	1991	1	0	0	1	0	0
5	Bridge5	1980	$5,000,000	2	divided	Steel	Interstate	6,000	10%	1995	1.2	0	0	1	0	0
6	Bridge6	1989	$6,000,000	6	divided	Steel	Otherstate	30,000	10%	1989	0.6	0	1	0	0	0
7	Bridge7	1975	$25,000,000	2	undivided	Concrete	Interstate	5,000	2%	2000	1	1	0	0	0	1
8	Bridge8	1987	$16,000,000	8	divided	Concrete	Interstate	50,000	5%		1.1	0	1	0	0	1
9	Bridge9	1980	$4,500,000	2	divided	Steel	Interstate	10,000		1990	0.5	1	0	0	1	0
10	Bridge10	2001	$10,000,000	8	divided	Steel	Interstate	90,000	10%		2.5	0	0	1	0	0

Figure 3: Main Worksheet for the Input Data

EXTENDED BRIDGE DECK MANAGEMENT SYSTEM

The basic BDMS has been extended to incorporate work zone planning into the decision support system. To do that, the spreadsheet system was modified to incorporate the user cost calculations as a function of the repair decisions (in Figure 4) and the work zone decision variables discussed earlier. Also, an optimization module was incorporated to select the optimum work zone strategy for each bridge during its repair time. The optimization module uses a powerful non-traditional technique, Genetic Algorithms (GAs), to arrive at near-optimum decisions for this complex and nonlinear problem.

Genetic algorithms are computerized search methods based on the theories of genetics and natural selection developed by Holland (1975). Typically, GA requires a representation scheme to encode feasible solutions to the optimization problem. Usually this is done in the form of a string called a chromosome. Each chromosome represents one member (i.e., one solution). The fitness of each chromosome is determined by evaluating its performance with respect to an objective function. To simulate the natural "survival of the fittest" process, one approach is to let best chromosomes exchange information to produce offspring chromosomes that are evaluated in turn and can be retained only if they are more fit than others in the population (Bishop et al. 1991). Usually, the process is continued for a large number of offspring generations in which the population gets enhanced and an optimum chromosome is arrived at.

Implementing the GA technique for the problem at hand involved four primary steps: 1) setting the solution representation (called chromosome); 2) deciding the evaluation criteria; 3) generating an initial population of solutions; 4) applying crossover/mutation to generate and test offspring chromosomes through cycles of evolution.

The chromosome structure is made of string of 4 elements (genes), each representing the number of days associated with one of the four work zone strategies, as shown in Figure 4. To evaluate a possible solution (chromosome), the objective function is to minimize the sum of user cost for each bridge along its planning horizon (Equation 2). Added to the objective function, the following constraints are considered:

- Total number of hours in work zone ≤ the expected duration;
- User predefined work zone strategy

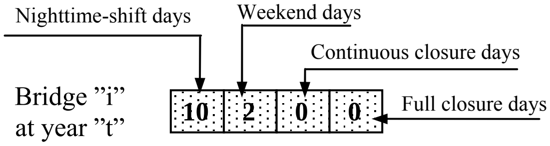


Figure 4: Solution Structure (Chromosome)

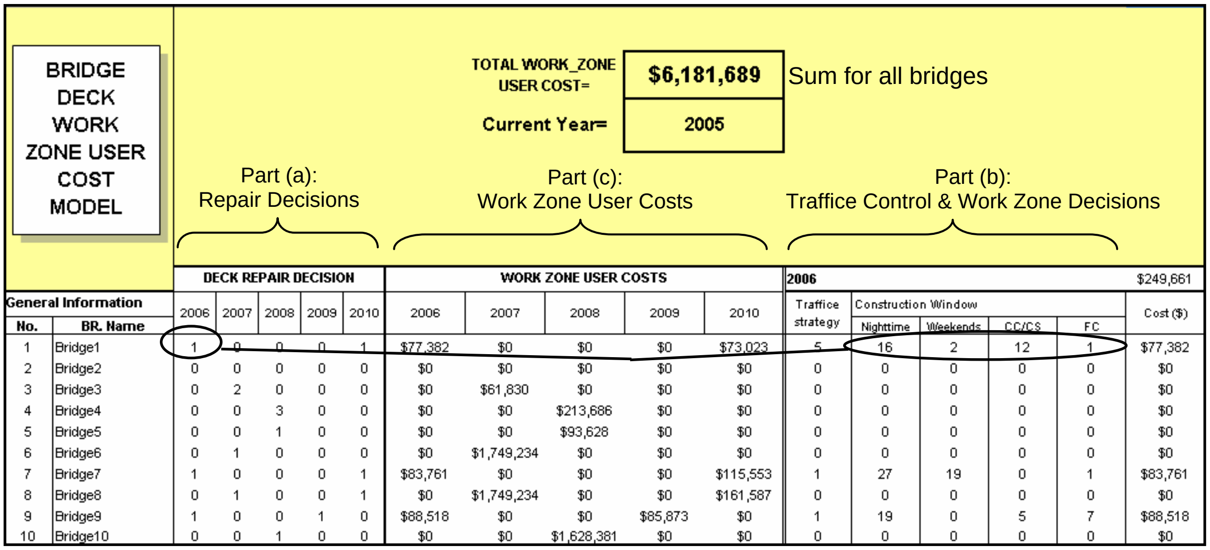
In the optimization, one additional condition was also specified to force the work zone strategy to be a full bridge closure in case of extensive deck repair (e.g., repair option 3). With the objective function and constraints defined, the GA procedure takes place on a population of parent solutions (chromosomes). The population is generated randomly, by assigning random values in each gene with a value from 0 to the maximum expected duration. Once the population is generated, the evolutionary process takes place, either by crossover (marriage) or mutation (Goldberg 1989). Many cycles (thousands) of offspring generations are then conducted and the population is evolved with more-fit solutions until an optimum solution is reached or a stopping criterion is met.

EXAMPLE APPLICATION

To illustrate the extended BDMS and its decision support for selecting work zone strategies, a simple example of ten bridges is considered. The initial bridge data, traffic data, and repair decisions are those previously shown in Figure 3.

Once the bridge data are input and the repair decisions are made through detailed life cycle cost analysis (Hegazy et al. 2004), the duration (in hours) for each repair work was estimated. Afterwards, the work zone optimization module was activated to determine the best work zone strategy to use with each bridge during its decided repair time. Accordingly, the evolutionary process was carried out until the stop criterion (no improvement in the objective function for 10 consecutive cycles) was met. The results of the current example are shown in Figure 5.

Part (a) in figure 5 shows the repair decisions for the bridge decks through the planning horizon; part (b) shows the bridges' traffic control plans and the optimized work zone strategies; and part (c) shows the work zone user costs associated with the decided strategies. For example, Bridge 1 uses the traffic control plan (TCP) no. 5 (Table 1) that suits a 4-lane bridge (Figure 5). Also, for the same bridge, the minor-repair decision in 2006 (highlighted in Fig. 5) mandates a work zone strategy (result of optimization) that is composed of 16 nighttime shifts, two weekends, 12 week-day continuous closure, and 1 day of full closure.



BRIDGE DECK WORK ZONE USER COST MODEL

TOTAL WORK_ZONE USER COST= $6,181,689 Sum for all bridges

Current Year= 2005

Part (a): Repair Decisions

Part (c): Work Zone User Costs

Part (b): Traffice Control & Work Zone Decisions

General Information		DECK REPAIR DECISION					WORK ZONE USER COSTS					2006					$249,661
No.	BR. Name	2006	2007	2008	2009	2010	2006	2007	2008	2009	2010	Traffice strategy	Construction Window				Cost ($)
													Nighttime	Weekends	CC/CS	FC	
1	Bridge1	1	0	0	0	1	$77,382	$0	$0	$0	$73,023	5	16	2	12	1	$77,382
2	Bridge2	0	0	0	0	0	$0	$0	$0	$0	$0	0	0	0	0	0	$0
3	Bridge3	0	2	0	0	0	$0	$61,830	$0	$0	$0	0	0	0	0	0	$0
4	Bridge4	0	0	3	0	0	$0	$0	$213,686	$0	$0	0	0	0	0	0	$0
5	Bridge5	0	0	1	0	0	$0	$0	$93,628	$0	$0	0	0	0	0	0	$0
6	Bridge6	0	1	0	0	0	$0	$1,749,234	$0	$0	$0	0	0	0	0	0	$0
7	Bridge7	1	0	0	0	1	$83,761	$0	$0	$0	$115,553	1	27	19	0	1	$83,761
8	Bridge8	0	1	0	0	1	$0	$1,749,234	$0	$0	$161,587	0	0	0	0	0	$0
9	Bridge9	1	0	0	1	0	$88,518	$0	$0	$85,873	$0	1	19	0	5	7	$88,518
10	Bridge10	0	0	1	0	0	$0	$0	$1,628,381	$0	$0	0	0	0	0	0	$0

Figure 5: Optimum Work Zone Strategies for the Example Bridges

The presented model in this paper has been demonstrated to work efficiently on the example application. Further experimentation with transportation agencies and municipalities are in progress to add practicality to the model at hand. Also, future extensions of the model are currently underway to refine the duration estimates for repair actions and also to incorporate the work zone user cost as a variable during the selection of repair decisions.

CONCLUSION

In this paper, a model was developed to support decisions related to the work zone strategy that minimizes user costs. The model uses genetic algorithms to arrive at near optimum solutions for this complex nonlinear problem. An example application was used to demonstrate the practicality of the model and its flexibility for various what-if analysis.

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