© Nottingham University Press
Proceedings of the International Conference on
Computing in Civil and Building Engineering
W Tizani (Editor)

Optimization of highway construction work zones: the agency and user cost tradeoff

Amr A. Kandil
Purdue University, USA

Khaled H. Hyari
Hashemite University, Jordon

Mayur Bisani
Black and Veatch, Australia

Abstract

The infrastructure renewal efforts taking place all over the world is creating a large volume of construction on highways and roads all over the globe. While these efforts are helping revitalize the ailing economies and infrastructures of nations, it comes with a cost to the traveling public. These costs present themselves in the form of prolonged congestions, and even more severely in the form of accidents leading to the death and/or injury of travelers. Previous research in this field has attempted to optimize each of these costs in isolation. Therefore, many studies have evaluated the cost of construction work zones to state highway agencies, and the corresponding costs to the traveling public. However, very few studies have evaluated the actual tradeoff between these two conflicting costs. The importance of creating these tradeoffs stems, not only from the responsibility that state highway agencies have towards the public, but also from the importance of public acceptance of the highway construction efforts taking place. Therefore, the objective of this paper is to develop a multi-objective decision support system that evaluates the tradeoff's between agency and user costs in the design of construction work zones. The model is designed to optimize work zone dimensions, configurations, closure times, and dates for two lane highways. The model utilizes a robust multi-objective evolutionary algorithm and is capable of finding the optimal tradeoffs between minimizing agency and user costs of the highway work zone. It is proposed that the developed model creates a much needed decision support tool that facilitates decision making in highway work zone design. In addition this model is hoped to increase public acceptance of highway work zones and all the nuisances they cause to the traveling public. The developed model was tested on a case study of a four lane high way, and was able to obtain several optimal solutions that show the tradeoff between user and agency costs.

Keywords: optimization, highway work zones, genetic algorithms, agency cost, user cost

1 Introduction

In recent years transportation agencies have started giving more importance to the 4R projects i.e. restoration, resurfacing, rehabilitation and reconstruction rather than building new facilities (Lee and Ibbs. 2004). The deterioration in the condition of the facilities prompted this shift because of decreasing road user safety and ride quality and the high increase in not only the vehicle operating costs but also overall maintenance costs of the pavement. During maintenance of multilane highways, lanes are closed to carry out the construction activities, consequently the traffic flow slows down and the capacity reduces. This could be avoided by improving decision making processes concerning project phasing and cycles. This fact motivated the authors to analyze the recently developed lane closure models, and optimization models to establish the importance of integrating decisions concerning lane closures.

Work zones in a two or more lane highway represent the section of the highway wherein one or more lanes are closed to perform the requisite maintenance, rehabilitation activities while the others are open for traffic. Since the number of lanes in use for traffic in both directions decreases, a feasible combination of lane length, queuing delays and the lane closure phase is required to minimize the user costs. Studies related to this topic are few and limited as far as their scope is concerned (Chien et al, 2002). These models addressed specific decisions that DOT's have to constantly make, and designed a wide spectrum of solutions in order to better manage different components of the transportation infrastructure. These models, however, attempted to optimize these decisions with some degree of isolation. For example, there are models to determine the optimum work zone length, optimum starting time of a work zone, and the construction time-cost tradeoffs for pavement repair and maintenance projects, but without considering the impact these decisions may have on each other (Chien et al. 2002; Jiang and Adeli 2003; El-Rayes and Kandil 2005) . The ideology behind this research is to combine traffic and construction management decisions to come up with integrated decision for any possible scenario and for all parties involved i.e. the agency, and the users. Therefore, this paper develops an integrated work zone optimization system using genetic algorithms that is designed to collectively optimize a number of major decisions concerning the maintenance and rehabilitation of a four-lane highway in order to find the optimum tradeoff between agency and user costs.

This paper starts with a review of some of the tools specifically developed to tackle the problems faced with respect to lane closure schemes. The paper then presents an optimization model which finds the best possible solution for a number of parameters vital in work zone management and minimizes the overall costs which include the sum of agency costs, user delay costs and accident costs.

2 Background

This section briefly discusses the models developed in the recent past and then moves on to describe the more recent attempts made in order to develop models for two lane and four lane highway with and without an alternate route. During maintenance of multilane highways lanes are closed to carry out the construction activities, consequently the traffic flow slows down and the capacity reduces. User delays can be caused because of reduced speed through work zones alone during off peak periods. Longer zones on one hand increase the user delays but at the same time with fewer repeated setups, maintenance activities can be performed with more efficiency. Most previous studies failed to find a joint optimum solution for traffic control and work zone lengths considering the maintenance costs incurred on two lane highways. Although some efforts jointly optimized work zone length and traffic control, they did not incorporate the accident costs (Chien and Schonfeld 2001). The road user delay costs have been mathematically modeled and analyzed in the past on the basis of some simplified assumptions in order to reduce the congestion and frustration experienced by drivers during freeway work zones. A model was developed by McCoy and Mennenga (1998) to find the optimum work zone length for minimum work zone costs in a rural four-lane freeway with one lane closure. The model considers the construction, user delay, vehicle operating cost, and accident cost on the basis of average daily traffic (ADT). Chien and Schonfeld (2001) developed a model using the ADT to estimate the delay cost and find the optimum work zone length in a four-lane freeway with one closure with the assumption that no queue can be formed if the capacity is more than the ADT. However since the traffic within a day or a season does not remain constant this assumption does not hold true for some part of the day (Jiang and Adeli 2003). A computer model called Queue and User

Cost Evaluation of work Zone (QUEWZ) was developed to determine the user costs, including delay costs and vehicle operating costs by estimating the average speeds in work zones. The number of hours available for lane closures along with a combination of various lane closures was based on an assumed lane capacity with fixed traffic volume. QUEWZ did not consider the effect of diverting traffic to an alternate route. Other systems such as EAROMAR and life cycle cost analysis tools are capable to analyze alternative project scopes and timings (Cambrige Systematics 2005).

Of particular interest to this study is the model formulated by Jiang and Adeli (2003) which dealt with two variables: the length of the work zone segment, and the starting time of the work zone using average hourly traffic data. More work zones are performed in the night to reduce the impact of construction activities on the road users. A factor α_n was introduced to take into account the effect of darkness. α_n was considered to be greater than one for construction work at night derived from previous experience and the management plan in practical application. The computation for accident cost considered two new parameters i.e. a darkness factor and number of lane closures. Two variables were considered during optimization; work zone length which is a real variable and starting time of the work zone in hours which is an integer variable. Boltzmann-simulated annealing neural network was developed to analyze the work zone cost optimization problem resulting from mixed real variable-integer. Numerical examples concluded that starting time of a work zone had an impact on queue formation and the total costs (Jiang and Adeli 2003). Thus in the proposed model a lot of emphasis was given on the preparation of an efficient traffic control plan, and the performance of what-if analyses that utilized the features of the model to the maximum.

3 Methodology

The objective of this paper is to develop a multi-objective optimization model that evaluates the tradeoffs between user and agency costs in highway construction work zones. Therefore, this paper will revisit the Jiang and Adeli (2003) model.

3.1 Model Objectives

The literature review helped identify the main parameters required for creating the multi-objective work zone optimization model. Jiang and Adeli (2003) have a comprehensive formulation to calculate the user delay costs. The equations listed in the paper by Jiang and Adeli (2003) were compared with the equations in Highway Capacity Manual (HCM) (2002) and it was found that the equations were based exactly on the HCM (2002) equations. In addition, in their paper Jiang and Adeli (2003) assume linearity between the work zone segment and the time and construction cost required to complete the project. Although this assumption is far from optimum, it was decided to base the new model on the same ideology presented by Jiang and Adeli (2003) and use the equations from the paper to calculate user delay costs, accident costs, and work zone construction costs. Construction costs are, however, going to be the subject of a more detailed analysis by the authors in a future research. One set of inputs for this model are traffic related data such as the Average Hourly Daily Traffic (AHDT) and work zone capacities for the work zones under consideration. The work zone capacity varies depending upon the number of lanes closed. In case all four lanes in one direction are closed then it is assumed that the traffic will be diverted into the lanes in the opposite direction with a median dividing the two way traffic. The work zone capacity in this case becomes half of the freeway capacity and the anticipated hourly traffic is doubled to account for traffic in both directions. By doing this, the resulting additional delays are calculated and optimum solutions are preserved. Based on this information the cumulative number of queuing vehicles can be calculated for any given hour after taking queue dissipation into consideration. The cumulative sum of queuing vehicles calculated during the time window for which the work zone will be closed for repair also known as the closure time helps calculate the queue delay, the moving delay and the associated user delay costs. All these calculations are dependent on the freeway capacity, the work zone capacity, the anticipated hourly traffic and the duration of closure time. The following table describes the user cost calculation parameters used in this model (Jiang and Adeli 2003):

Table 1 User Cost Calculation Parameters

Parameter	Symbol	Equation
Number of vehicles in a queue within a specific period	$Q_{\Delta t}$	$Q_{\Delta t} = \alpha_s f_{\Delta t} - c_w$
Cumulative number of vehicles in a queue	$T_{t+\Delta t}$	$T_{t+\Delta t} = \sum_{t=ti}^{t+t\Delta t} Q_{\Delta t}$
Queue delay time	t_q	$t_q = \sum_{t=ti}^{ti+D-1} (T_t + T_{t+\Delta t})/2 * \Delta t$
Moving delay over given period Δt (i) $(\alpha_s f_{\Delta t} > c_w)$ (ii) $(\alpha_s f_{\Delta t} < c_w)$	Δt_m	(i) $\Delta t_m = (1/V_w - 1/V_a) * l * c_w * \Delta t$ (ii) $\Delta t_m = (1/V_w - 1/V_a) * l * \alpha_s f_{\Delta t} * \Delta t$
Total moving delay time during the work zone duration	t_m	$t_m = \sum_{t=t_i}^{t_i+D-1} \Delta t_m$
Total user delay time	t_d	$t_d = t_q + t_m$
User delay costs per lane-kilometer	C_d	$C_d = c_{vh} * t_d / l * N_l$
Accident Cost per lane-kilometer	C_a	$C_a = \frac{\alpha_n n_a c_a t_d}{10^8 l \cdot N_l}$
Total User Cost per lane-kilometer	C_u	$C_u = C_a + C_d$

Where c_w= work zone capacity, V_w= work zone speed, V_a= approaching speed, $f_{\Delta t}$= number of vehicles approaching work zone during a period of time, α_s= seasonal demand factor, D= work zone duration, t_i= work zone start time, l = length of work zone segment, n_a= number of accidents per 100 million vehicle hours of delay, c_a= cost per accident, c_{vh}= average user cost per vehicle-hour, α_n= darkness factor accounting for working or driving at night.

In addition to the above described user costs, the developed model also aims to minimize the total cost of the maintenance to the owner agency. This total agency maintenance cost is calculated using the following equation.

$$C_m = \frac{\alpha_n c_1}{l \cdot N_l} + \alpha_n \cdot c_2 \quad (1)$$

Where c_1= fixed cost for work zone, and c_2= cost of maintenance per lane-kilometer.

Finally, the two objectives functions that are going to be optimized in the present model are going to be to simultaneously minimize total user costs (C_u) and the total maintenance cost of the work zone (C_m). The main decision variables that are going to be optimized in the present study are going to be the work zone length (l) and work zone start time (t_i). Since the model is mainly intended for optimizing short-term work zones (less than 24 hours long), the maximum work zone length is determined based on the amount of work that could be achieved in a 24 hour period. Also the start times for the work zone could be the start of any hour of the day (Jiang and Adeli 2003).

3.2 Multi-Object Optimization Algorithm

In order to establish the trade-off between work zone user and agency costs, a multi-objective genetic algorithm (MOGA) was utilized in this research. This MOGA is called the Non-dominated Sorted

Genetic Algorithm II (NSGAII). Research has demonstrated the robustness of this algorithm in addressing multi-objective optimization problems similar to the present user-agency cost trade-off problem (Reed et al. 2003, Deb 2001, El-Rayes and Kandil 2003). This algorithm is implemented in three main stages: (1) population initialization; (2) fitness evaluation; and (3) generation evolution (Deb 2001). The population initialization stage generates an initial population of virtual chromosomes that model a group of feasible start times and lengths for the work zone (work zone plans). This initial population is generated based on a number of parameters that are input in this function, including: (1) population size, which specifies the number of feasible solutions simultaneously evaluated by the genetic algorithm; (2) number of generations, which determines the number of times the genetic algorithm will iterate in order to find the optimal solutions; (3) crossover rate, which sets the probability of two virtual chromosomes crossing at a random point and exchanging their genes; and (4) mutation rate, which establishes the probability of genes in the virtual chromosomes would randomly changing their values. The values of these different parameters are determined using a set of parametric equations developed by Reed et al. (2003). The second stage of the implementation of the MOGA utilized in this case study establishes the relative merit of the different chromosomes in the genetic algorithm population. In order to perform this function each chromosome in this population is evaluated using the time and cost objective functions described above. These chromosomes were then ranked according to their nondomination. A solution that is identified to be nondominated, is a solution that is better than all the other work zone plans in the genetic algorithm population in at least one objective. The set of plans created by the nondominated plans is called the Pareto optimal set or front of solutions to the problem. Finally the population generation stage produced new genetic algorithm populations using the selection, crossover, and mutation processes (Deb 2001).

4 Results and Discussion

The above described MOGA was tested using a popular work zone scheduling problem obtained from the literature. The problem seeks to find the optimum work zone length and start time for a four-lane freeway with an average daily traffic (ADT) of 1000 vehicles per hour (vph). The work zone that needs to be schedules involves the closure of only one lane in one of the two directions of traffic. This problem was first analyzed by Chien and Schonfeld (2001), and then by Jiang and Adeli (2003). The following table shows the main user cost calculation parameters for this problem.

Table 2 User Cost Calculation Parameters

Parameter	*Value*
c_0	2,600 vph
c_w	1,200 vph
V_a	88.00 km/h
V_w	48.00 km/h
n_a	40 acc/100 mvh
c_a	$142,000/acc
c_{vh}	$12.00 /vph
c_1	$1,000/ zone
c_2	$80,000/km
N_L	1 lane
α_n	2.0
α_s	1.0

This example was analyzed using the developed MOGA and was able to find the same optimum solution as the Jiang and Adeli (2003) model, which has a start time of 8:00am and a work zone length of 0.35 km. However the developed model was also able to obtain 35 more Pareto optimal solutions that create a tradeoff between user and agency cost as show in Figure 1.

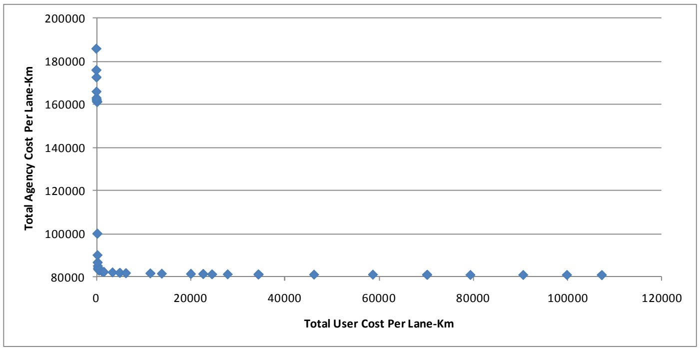

Figure 1. User-Agency Cost Trade-off

5 Conclusion and Future Research

The objective of this paper was to develop a multi-objective optimization model capable of analyzing the trade-offs between user and agency cost in highway construction work zones. This model was envisioned to be able to establish work zone lengths and start times that lead to the optimal tradeoff between these two costs. As such, a multi-objective genetic algorithm was developed for this purpose. This algorithm was tested using an example problem that was analyzed by a number of previous studies. In addition to obtaining the optimal results depicted by those studies, the present model was also able to obtain 35 Pareto optimal solutions to the problem, representing 35 different work zone start times and lengths. In ongoing and future research efforts, the authors wish to expand the scope of the present model to include long-term and multiple work zone closure schemes. The authors also plan to address construction cost and scheduling using a more detailed approach such as using discrete even simulation.

References

CAMBRIDGE SYSTEMATICS, Inc., PB CONSULT., SYSTEM METRICS GROUP, Inc. (2005). "Analytical tools for Asset management" *National cooperative highway research program Rep. No. 545*, Transportation Research Board, Washington, D.C.

CHIEN, S., TANG, Y., and SCHONFELD, P., 2002. Optimizing Work Zones for Two- Lane Highway Maintenance Projects. *J. Transp. Eng.*, 128(2), 145-155.

CHIEN, S. and SCHONFELD, P. 2001. Optimal Work Zone Lengths for Four-Lane Highways. *J. Transp. Eng.*, 127(2), 124-131.

DEB, K., 2001. Multi-Objective Optimization Using Evolutionary Algorithms, John Wiley, Hoboken, N. J.

EL-RAYES, K. and KANDIL, A., 2005. Time-Cost-Quality Trade off Analysis for Highway Construction. *J. Constr. Engrg. and Mgmt.*, ASCE, 131(4), 477-486.

HIGHWAY CAPACITY MANUAL (HCM), 2002. Transportation Research Record, National Research Council, Washington, D.C.

JIANG, X and ADELI, H., 2003. Freeway work zone traffic delay and cost optimization model. *J. Transp. Eng.*, 129 (3), 230-241.

LEE. E., and IBBS. C. W., 2004. Computer Simulation Model: Construction Analysis for Pavement Rehabilitation Strategies. *J. Constr. Eng. Manage.*, 131 (4), 449-458

MCCOY, P., T., and MENNENGA, D., J., 1998. Optimum length of single lane closures in work zones on rural four-lane freeway. Transp. Res. Rec. 1650, Transportation Research Board, National Research Council, Washington, D.C., 55-61.

REED, P., MINSKER, B., S., GOLDBERG, D., E., 2003. Simplifying multiobjective optimization: An automated design methodology for the nondominated sorted genetic algorithm-II. Water Resources Research, American Geophysical Union, 39 (7), 21-25.