A Simulation Model for Determining the Length of Two-Lane Urban Work Zones

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By:
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ABSTRACT

Unnecessary operations on ill-designed work zone would cause heavy monetary losses and also put users at tremendous inconvenience. Therefore proper design of maintenance work zones to accommodate traffic is very important. Previous studies have concentrated on the optimization of work zone in terms of work zone length by minimizing the total cost comprising user and construction cost. This study extends the existing literature by proposing a discrete stochastic event simulation model, which considers the randomness associated with the arrival process. Simulation is done for a variety of different cases and the results are tabulated after performing output analysis to determine the confidence intervals for the various performance measures.

Key Words: Work zone, simulation model, optimal length, traffic delay.
INTRODUCTION

The network of interstate highways in the United States has reached maturity, and the construction of new highways across the country has almost ended. Because the interstate highways reach the end of their serviceable lives, reconstruction, maintenance, and rehabilitation has become more common. However, highway maintenance is very expensive not only in terms of agency costs but also in terms of delays to the traffic and in general to the drivers. Maintenance work zones have significant impacts on existing operations, including reduced roadway capacity, increased accident rates, increased fuel consumptions and additional congestion and delay.

According to Graham-Migletz enterprises, Inc. (1) the work zone type depends on the basic layout of a work site. There are eight basic zone types (work sites that do not disrupt traffic are not considered):

1. Lane Constriction.
2. Lane Closure.
4. Temporary Bypass.
5. Intermittent Closure
6. Crossover.
7. Use of Shoulder or Median.
8. Detour.

In this work we concentrated mainly on the most widely used type of work zone, the Shared Right of Way.

PROBLEM STATEMENT

Maintenance, construction or rehabilitation activities on urban streets and on highways are difficult to schedule because direct and indirect costs affect the availability of work time to
perform these activities. In this analysis the overall project cost consists of two components: maintenance cost and user delay cost as a function of the length of the work zone. Usually the best action to minimize the first cost component would be to close off the entire roadway so that construction workers can perform their work unaffected by passing traffic and drivers are not involved in the construction work zone hazards. However, the complete shutdown of the traffic is often not a reasonable way to reduce costs because it can rapidly increase traffic and congestion. Therefore, the problem can be seen as a trade-off between reducing maintenance cost and mitigating user delay costs so that the resources are expended in the most cost-effective way possible. This paper develops a simple and practical method for determining the optimal work zones lengths that minimize the total cost which consists of maintenance cost and user delay cost for two-lane highways.

LITERATURE REVIEW
Several studies have dealt with determining the optimal length of work zones in the United States. These studies have investigated different methods of optimizing work zone traffic control characteristics. This study delves into the stochastic nature of the traffic, and provides an automated procedure for determining the optimal work zone length for two-lane highways.

Rouphail and Tiwari (2) is one of early papers in the literature that analyzed freeway traffic speed flow at single closures. The authors develop a procedure to isolate the impact of the work zone. They concentrate on the location of work relative to road lanes, employers, type of equipment, noise and work zone length. The results of their research show that the work zone activities have effect on traffic flow especially in peak hours, high heavy vehicles percentages, and work activities near the traveled lanes.

Rouphail and Nemeth (3) developed a microscopic simulation model that is based on the principle that all vehicles are controlled by a car following rules. The model is developed to
study traffic behavior under a variety of conditions represented by margining preferences speed control, and warning distances. The model focuses on behavioral aspects of drivers (for e.g. response to warning signs) and shows that at low speeds drivers are not affected by the warning devices at the site.

Memmott and Durek [4] discussed QUEWZ (Queue and User Cost Evaluation of Work Zones) model that estimates the additional user costs resulting in the case that we have to close a lane in one or both directions of travel. In the paper the user costs are divided based on the capacity through the work zone in four general categories. Delay costs, vehicle running costs, speed change costs, and accident costs are the four major categories that the paper considers. These costs are affected by different components such as delay time, volume, and difference in speed due to the work zone area. However, the model does not include the accident cost during the work zone activities, and does not include techniques to avoid queues in the work zone.

Jiang (5) proposed a new model to estimate excess user costs at work zones in terms of fuel consumptions, travel time, and automobile parts. Jiang’s research concludes that during congestion at work zones delay costs are relatively close to total excess costs. In addition, reduced speed, delay costs, and excess running costs due to speed changes could considerably contribute to the total excess user costs in long work zones.

Mousa, Azadivar, and Rouphail (6) presented a methodology to optimize performance of a traffic system on the basis of simulated observations of its microscopic behavior. They integrate simulation and optimization sub models to describe traffic flow on urban freeway lane closures. The objective is to recommend the lowest average travel time in work zone.

Chen and Schonfeld (7) developed a mathematical model to optimize work zone lengths. The objective of their study is to minimize total costs, and delay costs. The optimization model is developed deterministically and the stochastic nature of arrival process is not given much importance.
Chen et al., (8) evaluated several alternatives defined by the number of closed lanes and fractions of traffic diverted to alternate routes. The SAUASD (Simulated Annealing for Uniform Alternatives with a Single Detour) algorithm is developed to find the best single alternative throughout a resurfacing project. The SAMASD (Simulated Annealing for Mixed Alternatives with a Single Detour) algorithm is developed to search through possible mixed alternatives and their diverted fractions in order to further minimize total cost, including agency cost (resurfacing and idling cost) and user cost (user delay cost and accident cost). Thus, traffic management plans with uniform or mixed alternatives are developed for a two-lane highway resurfacing project.

The aim of our study is to develop a discrete event stochastic model that can be used as a tool to arrive at optimal work zone length under various traffic situations. Several cases will be analyzed to study the effect of different traffic conditions.

THE MODEL

The proposed methodology described in this section will be used to determine scenarios (cost-effective schedules) of maintenance activities to be performed in urban highways. These scenarios are expected to minimize the maintenance cost and the delay cost. We will study various cases that can be evaluated in real traffic conditions using simulation. Two general configurations of lane closures through a work zone are incorporated into the model. The first configuration involves situation where one lane in one direction is closed, which affects the opposite traffic moving.

We use a random-arrival generator (Linear Congruential Generator) was developed for generating the random inter-arrival times. The stochastic nature of the arrival process is represented by a Poisson distribution. Maintenance work is controlled either by stop signs or by traffic signals designed in a similar way as those at standard intersections.
The major components affecting the total cost function depend on various important factors such as: the work zone length, speed reductions due to maintenance activities and in case of two-lane highway, the period of time when a direction is given green since delays are incurred during red periods.

We propose a microscopic simulation model to evaluate the cost-effectiveness of using improved traffic control plans at urban roadway network. Computer simulation provides data required for cost analysis that would be difficult to get from other resources. It is also important to limit the system computation time. Therefore, for this work we did not use any existing software such as TSIS/FREESIM. The simulation model represents an urban roadway with lane closures. The simulation model is successfully interfaced with a procedure to get better traffic solutions. This event-based simulation model is developed in C++ in windows environment, and it is successfully interfaced with a procedure to obtain solutions. The roadway characteristics in the simulation model are represented by a system of lengths and widths. The model is designed to handle two-lane and four-lane roadways using alternative traffic management plans to determine delay. The overall logic of the simulation model for two-lane is shown in the flowchart in Figure 1.
FIGURE 1 Simulation Flow Chart For Two-Lane Roadways.
Most of the previous work in this topic uses ADT as input data. However, the daily peaking pattern can have a significant impact on average speeds and queues during the day as mentioned by Memmott and Dudek [6]. In this model we specify the arrival distribution.

The optimization process comprises of simulating for different work zone lengths and finally finding the length that is associated with the minimum total costs per ft. Different constraints can be (a) minimum lengths for the green periods, (b) maximum lengths for the green periods, and (c) minimum and maximum values for the length of the work zone.

MODEL APPLICATIONS

The microscopic simulation model developed in the course of this study has two applications at work zone sites:

- Comparing field performances for different traffic situations.
- Designing efficient traffic system for optimal performance of the traffic.

In this research we study a two-lane roadway by closing one lane that is under construction. This scenario is examined under different traffic situations. Four cases are developed that are mainly for illustrating the concept and logic of this research.

1. **CASE-1**: mean inter-arrival time of 10 sec and 60 sec effective green time for both directions.
2. **CASE-2**: mean inter-arrival time of 20 sec and 60 sec effective green time for both directions.
3. **CASE-3**: mean inter-arrival time of 10 sec for one direction and 20 sec for the other direction and 60 sec effective green time for both directions.
4. **CASE-4**: mean inter-arrival time of 5 sec for one direction and 10 sec for the other direction and effective green time of 40 sec for one direction and 50 sec for the other direction.
The main idea in this application is to perform multiple replications to obtain realistic values. Different seeds are used for performing independent replications. For Common Random Numbers (CRN), the same seeds were used to perform multiple replications. Please note that the System (Construction) Cost consists of two parts – Fixed and Variable. Since all costs were calculated per ft, the fixed costs in the figures would add an offset to the y-axis, which would make the interpretation difficult. Hence the fixed cost is not shown. Moreover the variable cost is more interesting as it changes with the work zone length. Figure 2 shows the average total cost per ft for different work zone lengths using different seeds and the mean inter-arrival times equal to 10 sec for directions 1 and 2 and the green times equal to 60 sec for each direction. Figure 2 depicts the total cost per ft and delay costs per ft for CASE 1. Note that only one replication is shown in this figure.

**Average of Total Cost($) per ft for 10 Replications for CASE 1:** (ma1=10, ma2=10, g1=g2=60)

![Graph showing the average of total cost per ft for 10 replications for CASE 1.](image)

**Legend:**
- **m**a1 = Mean Inter-arrival time in Sec for Direction 1.
- **g**1 = Green Time for Direction 1.
- **m**a2 = Mean Inter-arrival time in Sec for Direction 2.
- **g**2 = Green Time for Direction 2.

**FIGURE 2** Results from Multiple Replications for CASE 1.
Table 1 shows different measures of performance for ten replications using different seeds when mean arrival times are 10 sec each and green periods are 60 sec each. Optimal lengths are also mentioned for this situation. Table 1 shows the result of each replication. The performance measures of interest are the average vehicle time in the system, the average vehicle time in queue, and the average number of vehicles in queue.

We construct the 95% confidence interval for each performance measure as shown in Table 1. Note that in the calculation of confidence intervals, the following formula is used:

\[ X(n) \pm T(n-1, 1-\alpha/2) \frac{\sigma}{\sqrt{n}} \] (9)

**TABLE 1.** Performance measures for CASE 1 for Two-Lane Roads.

<table>
<thead>
<tr>
<th>Replication</th>
<th>Optimal Length(ft)</th>
<th>Average time in Queue 1</th>
<th>Average time in Queue 2</th>
<th>Average time in System 1</th>
<th>Average time in System 2</th>
<th>Average number in Queue 1</th>
<th>Average number in Queue 2</th>
</tr>
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<tbody>
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<td>1</td>
<td>1690</td>
<td>117.2</td>
<td>119.4</td>
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<td>214.7</td>
<td>11.5</td>
<td>11.7</td>
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<td>123.4</td>
<td>124.1</td>
<td>227.0</td>
<td>227.8</td>
<td>12.1</td>
<td>12.1</td>
</tr>
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<td>3</td>
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<td>119.6</td>
<td>122.2</td>
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<td>11.5</td>
<td>12.0</td>
</tr>
<tr>
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<td>12.4</td>
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<td>1950</td>
<td>126.4</td>
<td>128.6</td>
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<td>12.3</td>
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</tr>
<tr>
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<td>1990</td>
<td>127.8</td>
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<td>240.4</td>
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<tr>
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<td>1640</td>
<td>115.9</td>
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<td>11.6</td>
<td>11.1</td>
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<td>1750</td>
<td>120.8</td>
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<td>219.5</td>
<td>219.5</td>
<td>11.9</td>
<td>11.9</td>
</tr>
</tbody>
</table>

Mean 1817 122.0 123.4 224.4 225.7 12.0 12.1
Variance 1300 1.1 15.4 16.2 104.8 107.2 0.2 0.3
S.D. 114.2 3.9 4.0 10.2 10.4 0.4 0.5
95% Half Length 80.3 2.8 2.8 7.2 7.3 0.3 0.4
CF(in ft) LL 1736.7 119.3 120.6 217.2 218.5 11.7 11.8
CF(in ft) UL 1897.3 124.8 126.2 231.6 233.0 12.2 12.5
CF(in m) LL 526.3
CF(in m) UL 574.9

*S.D. stands for Standard Deviation
*CF stands for Confidence Interval, LL=Lower Limit, UL=Upper Limit
Similar output analysis was done for CASE 2 and the results are tabulated in Table 2. Confidence intervals for other performance measures are also calculated and these values are indicated in Table 2. We can see that in CASE 1, we have the optimal length as 1817 ft with CI for it being (~1736, ~1897). In the second CASE, we have the optimal length being equal to 1828 ft with CI equal to (~1710, ~1945).

**TABLE 2 Performance Measures for CASE 2 for Two-Lane Roads.**

<table>
<thead>
<tr>
<th>Replication</th>
<th>Optimal Length(ft)</th>
<th>Average time in Queue 1</th>
<th>Average time in Queue 2</th>
<th>Average time in System 1</th>
<th>Average time in System 2</th>
<th>Average number in Queue 1</th>
<th>Average number in Queue 2</th>
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<td>225.3</td>
<td>5.8</td>
<td>5.9</td>
</tr>
<tr>
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<td>1790</td>
<td>116.8</td>
<td>120.8</td>
<td>217.6</td>
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<td>6.8</td>
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<tr>
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<td>1700</td>
<td>114.3</td>
<td>115.3</td>
<td>210.1</td>
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<td>5.8</td>
</tr>
<tr>
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<td>1550</td>
<td>109.3</td>
<td>112.0</td>
<td>196.8</td>
<td>199.5</td>
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<tr>
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<td>1940</td>
<td>124.3</td>
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<td>6.1</td>
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<td>10</td>
<td>1940</td>
<td>125.9</td>
<td>123.9</td>
<td>235.1</td>
<td>233.1</td>
<td>6.3</td>
<td>6.2</td>
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</tbody>
</table>

Mean Length: 1828 ft  
Variance: 27662.2  
S.D.: 166.3  
95% Half Length: 117.2 ft

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>Average (in ft)</th>
<th>Average (in m)</th>
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<tbody>
<tr>
<td>CF (in ft) LL</td>
<td>1710.8</td>
<td>518.5</td>
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<tr>
<td>CF (in ft) UL</td>
<td>1945.2</td>
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</table>

Also, we have output analysis for CASE 3 and the results are reported in Table 3, which it shows different measures of performance for ten replications using different seeds when mean arrival times are 10 sec each and green periods are 60 sec each. Optimal lengths are also mentioned for this situation. Table 3 shows the result of each replication. The performance
measures of interest are the average vehicle time in the system, the average vehicle time in queue, and the average number of vehicles in queue.

TABLE 3 Performance Measures for CASE 3 for Two-Lane Roads.

<table>
<thead>
<tr>
<th>Replication</th>
<th>Optimal Length (ft)</th>
<th>Average time in Queue 1</th>
<th>Average time in Queue 2</th>
<th>Average time in System 1</th>
<th>Average time in System 2</th>
<th>Average number in Queue 1</th>
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<td>121.2</td>
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<td>11.6</td>
<td>6.0</td>
</tr>
<tr>
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</tbody>
</table>

Mean: 1808 121.7 120.6 223.7 222.5 11.9 6.0
Variance: 15262.2 15.8 20.8 113.7 125.6 0.2 0.1
S.D.: 123.5 4.0 4.6 10.7 11.2 0.4 0.3
95% Half Length: 87.1 2.8 3.2 7.5 7.9 0.3 0.2
CF (in ft) LL: 1720.9 118.9 117.4 216.2 214.6 11.6 5.8
CF (in ft) UL: 1895.1 124.5 123.8 231.2 230.4 12.2 6.3

CF (in m) LL: 521.5
CF (in m) UL: 574.3

*S.D. stands for Standard Deviation
*CF stands for Confidence Interval, LL=Lower Limit, UL=Upper Limit

In addition we have output analysis for CASE 4 and the results summarized in Table 4.
TABLE 4 Performance Measures for CASE 4 for Two-Lane Roads.

<table>
<thead>
<tr>
<th>Replication</th>
<th>Optimal Length (ft)</th>
<th>Average time in Queue 1</th>
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<th>Average time in System 1</th>
<th>Average time in System 2</th>
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<td>1840</td>
<td>112.0</td>
<td>110.2</td>
<td>215.6</td>
<td>213.8</td>
<td>22.6</td>
<td>10.6</td>
</tr>
<tr>
<td>10</td>
<td>1850</td>
<td>112.1</td>
<td>109.0</td>
<td>216.3</td>
<td>213.2</td>
<td>22.0</td>
<td>10.9</td>
</tr>
</tbody>
</table>

Mean 1837 111.7 109.6 215.2 213.1 22.0 10.8
Variance 6890.0 11.7 6.7 64.3 49.2 0.6 0.1
S.D. 83.1 3.4 2.6 8.0 7.0 0.8 0.4
95% Half Length 58.5 2.4 1.8 5.7 4.9 0.5 0.3
CF (in ft) LL 1778.5 109.3 107.8 209.5 208.1 21.5 10.6
CF (in ft) UL 1895.5 111.4 111.4 220.8 218.0 22.6 11.1

S.D. stands for Standard Deviation
*CF stands for Confidence Interval, LL=Lower Limit, UL=Upper Limit

CASE 1 considers the inter-arrival means for direction one (1) equal to 10 sec and for direction two (2) equal to 10 sec. The effective green period for first direction is 60 sec and for the second direction is also 60 sec. Total cost is higher initially as the construction cost is very high as expected, but for longer work zones, the increase is very small as can be seen in Figure 3.
CASE 1 can be observed in Figure 3. The effective green period for the first and second direction is 60 sec. Also, the total cost is higher initially as the construction cost is very high as expected, but for longer work zones, the increase is very small as can be seen in Figure 4.

CASE 2 can be observed in Figure 4. The effective green period for the first and second direction is 60 sec. Also, the total cost is higher initially as the construction cost is very high as expected, but for longer work zones, the increase is very small as can be seen in Figure 4.
Also, CASE 3 and CASE 4 produce similar results that are shown in Figures 5 and 6.

**FIGURE 5** Optimal Lengths and Costs- CASE 3.

**FIGURE 6** Optimal Lengths and Costs- CASE 4.
From Tables 1-4 one can note that in CASE 1, the optimal mean length is 1817 ft, in CASE 2 it is 1828 ft, in CASE 3 the value is 1808 ft, and in CASE 4 it is 1837 ft. Queue Lengths in the four cases are: In Case 1 in both directions the Queue length is 12 vehicles, in Case 2 in both directions the Queue length is 6 vehicles, in Case 3 in one direction the Queue length is 12 vehicles and for the second direction is 6 vehicles, and in Case 4 in one direction the Queue length is 22, and for the second direction the Queue length is 11 vehicles. CASE 4 represents the highest approaching flow, with CASE 2 depicting the lowest approach traffic. And accordingly, CASE 4 represents a situation where queue lengths are higher compared to CASE 2 where queue lengths are the lowest. And also note that Standard Deviation in work zone length is highest in CASE 2 whereas in CASE 4 it is lowest. Thus, during peak-hours model gives a tighter bound for the optimal work zone lengths, whereas lesser traffic flow gives a weaker bound for the optimal work zone length. Average delay amounts to the same in all the cases with a much lesser difference across the cases.

In this study, many runs were made under traffic conditions to understand the behavior of work zone length with various costs, inter-arrival times and green times. Different inter-arrival times like 3 sec, 10 sec, 15 sec, 20 sec etc for each direction and different green times like 60sec, 100sec etc were considered. For example one particular situation would be 3 sec inter-arrival time for one direction with a green time of 100 sec, and the inter-arrival in the other direction is varied from 3sec – 20 sec, with green time of 100sec. As the flow increases (decrease in the inter-arrival times), the work zone length increases. However, as the zone length, the maintenance cost decreases since fewer setups. As the user cost is increased, the work zone length increases. Hence, the problem can be seen as a trade-off between the user and maintenance cost. This analysis shows that as the traffic flow increases over time, appropriate work zone length offers a way to balance the costs from the perspective of the user and the system. Figure 7 represents a concise number of situations for different scenarios.
LEGEND: First value represents the inter-arrival time in sec for direction 1. Second value represents the green time in sec for direction 1. Third value represents the inter-arrival time in sec for direction 2. Fourth value represents the green time in sec for direction 2.

FIGURE 7 Representation of different traffic situations.

A similar study is conducted for a four-lane roadway under different traffic conditions when one or two lanes closed due to construction. The specific situation reported has involved two-lanes in each direction when one lane is closed. A model is developed, but results would be reported in the future.

From a theoretical perspective, simulation-based models being stochastic in nature cannot give a single optimal value. This research tried to understand the implications of the randomness associated with the arrival process on the optimal length under different traffic conditions. As discussed previously, in some cases, there were tighter bounds, which from practical considerations, help in providing a better work zone management plan.
CONCLUSION AND FUTURE STUDIES

A model was presented to calculate the user cost and the delay cost generated by restricted capacity through a work zone. The proposed modeling approach demonstrates how work zone lengths can be obtained based on all of the important factors affecting such maintenance decisions for two-lane roads. The sensitivity analysis shows that if traffic flow increases the maintenance cost increases as well. The total cost for maintaining a two-lane roadway without an alternative route is significantly higher than with such an alternate route. The major difference is that the cost in the first case, is higher than the second case because the queue is formed and drivers cannot avoid delays caused by maintenance activities. In general traffic delays due to work zones can be classified as speed reduction delay (moving delay) and congestion delay (stopping delay).

Traffic delay due to a work zone can be reduced by decreasing the length of the work zone or changing the roadway closure pattern because total delay increases with the length of a work zone. However, reducing the length of a work zone will increase the delay cost at the project level. Finally the model can be applied to determine the optimal length of the construction and determine whether speed has any affect on delay for certain ranges of traffic volumes.

Modifications to the assumptions presented in this work to evaluate additional situations can be viewed as a significant area for future research.
REFERENCES


