A Modified Arc Routing Problem for Highway Feature Inspection Considering Work-Shift and Overtime Limit Constraints

MANOJ K. JHA, FRANCIS UDENTA, SIMON CHACHA, GAUTHAM KARRI
Department of Civil Engineering
Morgan State University
1700 East Cold Spring Lane, Baltimore, MD 21251
USA

Abstract: Transportation problems are often defined in terms of delay and efficiency. In order to keep pace with deterioration of various elements within the transportation system especially highway appurtenances, it is expedient to monitor them periodically to evaluate their conditions. Valuable information obtained from such exercises drive subsequent actions to repair or replace these elements and keep highway appurtenances functioning as expected. Various past research efforts concentrated on highway maintenance optimization for pavements and other highway structures like bridges and drains. The recognition of the essence of highway road features in the overall safety of the highway system has yielded recent limited research efforts on strategies for optimizing maintenance of highway appurtenances. The efforts however, lack extensive work in the area of Maintenance Inspections (MI) for highway appurtenances. In practice, highway maintenance inspections occur within work-hour shifts in many government agencies and are often left to the inspector to schedule and organize his route. The inspector must leave from and return to a particular location (the office or yard) at the end of the work-shift. The implication is that the inspector spends a good portion of the work-shift traveling. This causes a cumulative waste of time and resources, and a huge cost to the taxpayers. In this paper we introduce a modified Arc Routing approach to a cost minimization inspection problem. We consider work-shift and overtime constraints in developing an efficient shortest path for implementing inspection schedules within a specified location. A unique algorithm is developed for solving the optimization model. The consequent solution is applied to real location in Baltimore, Maryland. Finally, a direction for future works is presented.

Key-Words: Highway inspection, Arc routing, work-shift, overtime, optimization, shortest path algorithm.

1 Introduction
Highway inspection as well as maintenance reconstruction and rehabilitation (M R & R) should be done economically. More often in a highway network there are numerous segments (divided, undivided, one-way, two-way) see figure 1a and 1b that need to be inspected at routine intervals before appropriate M R & R actions can be undertaken. This paper deals with the development of a mathematical formulation and solution algorithms to the highway feature inspection optimization while considering work shift and overtime limit constraints. In previously published works, work shift and overtime constraint were not comprehensively considered. Jha et al applied genetic algorithm in developing a decision support system to choose the best economical route for maintenance inspection. However, the return path

Figure1. A Typical Highway Segment in Baltimore, Maryland
condition was not taken into account. This leaves a huge void in ensuring policy compliance when attempting to implement the model. This paper takes the return arc and travel time into account as well as possible overtime considerations in determining the shortest path. In practice highway maintenance inspections occur within specified work shifts (such as 8-hour work day) in highway agencies. It is often left to the inspector to schedule and organize the inspection route for a given work-shift. The inspectors must leave from and return to a particular location (office or yard) at the end of the work-shift. The implication is that the inspector spends a good portion of the work-shift traveling. This causes a cumulative waste of time and resources, which translates to great costs to taxpayers.

This paper provides a modified arc routing formulation based on work-shift and overtime constraints. A probable solution using the shortest path algorithm will provide an insight on tackling a real life situation. A hypothetical shortest path example, based on a real case scenario will be presented followed by conclusion, recommendation and direction for future work.

2. Problem Formulation

2.1 Current Practices

Most urban cities and counties have somewhat similar practices in how they approach inspection of highway infrastructures. They provide a strict work shift and provide vehicles that must be returned at the end of the work shift. Their policies generally discourage overtime. For clarity of perspective we will discuss current policies and practices in Baltimore City, Maryland.

Baltimore City runs 8-hour work-shifts. Inspectors work in four (4) sectors: north-east, north-west, south-east and south-west. The quadrants are divided along Charles Street from north to south and along Baltimore Street from east to west. Each section is overseen by an inspector. The inspectors effectively use 6 hour within the work-shift for inspections on highway infrastructures such as pavement, bridges, road signs, guardrails and luminaries. These include inspections resulting from routine complaints and periodic maintenance inspections. Given budgetary and funding constraints, urban cities such as Baltimore City must prioritize its maintenance activities. The City launched operation orange cone in 2007 to put the City in the path of achieving its road repair and reconstruction goals. The focus of routine maintenance inspections are on major arterials. Secondary roads are not considered for this paper.

1.1 Literature Review


Figure 2. A typical urban network

WSEAS International Conference on URBAN PLANNING and TRANSPORTATION (UPT’07), Heraklion, Crete Island, Greece, July 22-24, 2008
2.2 Formulation Assumptions

Routing highway maintenance inspections is similar to the Chinese Postman Problem. In this paper, we account for the limits (capacity) on the arcs therefore formulate the inspection routing problem as Capacitated Arc Routing Problem (CARP). To simplify the formulation, we have modified the CARP problem with the following assumptions:

(i) The inspection crew is paid for eight (8) hours regular time
(ii) The daily route is chosen such that inspection is completed in eight (8) hours with minimal overtime
(iii) Each arc can only be inspected once
(iv) Each arc can be traveled multiple times
(v) A valid tour contains the shop node twice
(vi) A valid tour contains arcs that connect the shop

2.3 Formulation

Let \( Y = (V, A) \) be a directed graph with \( n+1 \) nodes of a network to be inspected (including the starting node (node 1) where the crew starts its inspection from). Each arc \((i, j) \in A\) represents a segment between two intersections. For clarity a forward arc \((i, j)\) represents movement from origin (office or yard) while backwards arc \((j, i)\) represents movement back to origin. Within a work-shift, \( T \) the time required to traverse a given arc \((i,j)\) is \( t_{ij} \), while the time required to complete the necessary inspections along the arc is \( c_{ij} \).

Figure 3 A typical network showing a shop node.

\[
y_{1ij} = \begin{cases} 
1 & \text{if arc } (i, j) \text{ is traversed or inspected} \\
0 & \text{Otherwise}
\end{cases}
\]

\[
y_{2ij} = \begin{cases} 
1 & \text{if } T > 8 \\
0 & \text{Otherwise}
\end{cases}
\]

Based on the above, the objective function for the shortest path problem can be formulated as follows:

\[
\begin{align*}
\min & \sum_{i,j \in A} \sum_{r=1}^r \left( t_{ij} + t_{2ij} \right) c_{ij} y_{1ij} x_{ij}^r + \\
& \sum_{i,j \in A} \sum_{r=1}^r \left( T - t_{1ij} - t_{2ij} \right) c_{ij} y_{2ij} x_{ij}^r 
\end{align*}
\]

Subject to,

\[
\sum_{k \in N} x_{ki} - \sum_{k \in N} x_{ik} = 0, \forall i \in N, r = 1,2,\ldots, r
\]

\[
\sum_{r=1}^r y_{1ij}^r \sum_{r=1}^r y_{2ij}^r = 1 \quad \forall (i, j) \in A
\]

\[
y_{1ij} = \{0,1\} \quad \forall (i, j) \in A
\]

\[
y_{2ij} = \{0,1\} T > (t_{1ij} + t_{2ij}) \quad \forall (i, j) \in A
\]

\[T,C_{1ij},C_{2ij},t_{1ij},t_{2ij},y_{1ij},y_{2ij},x_{ij} \geq 0\]

Non-negativity constraint

Where;

\( A \): Set of arcs
\( V \): Set of nodes
\( C_{1ij} \): Hourly cost in regular time ($/hr)
\( C_{2ij} \): Hourly cost in over time ($/hr)
\( t_{1ij} \): Time to traverse arc \((i,j)\)
\( t_{2ij} \): Time to inspect arc \((i,j)\)
\( T \): Cumulative work-shift duration
\( y_{1ij} \): 1 if arc \((i,j)\) is traverse or inspected, 0 otherwise at regular time
\( y_{2ij} \): 1 if arc \((i,j)\) is traverse or inspected, 0 otherwise at overtime.
The objective function expressed in equation (1) minimizes total travel time required to traverse an arc and complete the necessary inspections. Equation (2) and (3) define time needed to traverse an arc and the time used to complete inspection along the arc respectively. Equation (4) guarantees that inspection occurs along each arc at least once. Equation (5) states that an arc must be traversed and inspected during work-shift, \( T \) and the overtime constraint is given in equation (6). Equation (7) is the non-negativity constraint.

3 Problem Solution

The general solution approach is heuristic. We consider real life conditions at specific location in Baltimore, Maryland. Solution approach is two-tier: first we use Floyd-Warshall method to determine the shortest path, feasible network and optimal values for the travel time and inspection time. The values shown in Table 1 are the optimal total time for the network shown in Figure 3.

<table>
<thead>
<tr>
<th>Arc</th>
<th>Travel Time (min)</th>
<th>Inspection Time (min)</th>
<th>Total Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25</td>
<td>45</td>
<td>70</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>35</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>25</td>
<td>35</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>5</td>
<td>30</td>
<td>45</td>
<td>75</td>
</tr>
<tr>
<td>6</td>
<td>17</td>
<td>35</td>
<td>52</td>
</tr>
<tr>
<td>7</td>
<td>25</td>
<td>45</td>
<td>70</td>
</tr>
<tr>
<td>8</td>
<td>35</td>
<td>50</td>
<td>85</td>
</tr>
<tr>
<td>9</td>
<td>25</td>
<td>45</td>
<td>70</td>
</tr>
<tr>
<td>10</td>
<td>15</td>
<td>35</td>
<td>50</td>
</tr>
</tbody>
</table>

The above optimal values can be plugged into to objective function to obtain the optimal cost for efficiently covering all the arcs in a timely manner. For more complex networks, we can develop a solution model using Genetic Algorithm by combining the formulation assumption and the constraints. The steps for the program for the solution model are as follows:

Step 0 Give an integer between 1 and \( n \), \( n_j \)
Step 1 If \( n_j < 3 \), then go to Step 0
Step 2 Random generate \( n_j \) nodes
Step 3 Check if tour is valid otherwise go to Step 2

Figure 4 shows a typical highway network in Maryland. We can apply the resulting model in establishing to most efficient way to inspect the network at minimal cost while taking into account work-shift and overtime constraints.

4 Conclusion

Considering the effect of the attributes of a shop node within a highway network and constraints imposed by the work-shift and overtime, highway maintenance inspections can be routed in a cost efficient manner. Optimization of time in performing inspection activities translates to direct optimization of resources and drastic reduction of waste. However other aspects of planning such as scheduling must be in place for the true impact of this research to be fully appreciated. Consequently, we recommend further research in highway maintenance inspection scheduling.
References:

State the benefits to your audience for taking this action


