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Formulation and solution algorithms for highway infrastructure maintenance optimisation with work-shift and overtime limit constraints

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Abstract

This paper deals with the issue of highway infrastructure maintenance which is indirectly related to city logistics since for efficient city logistics, operation highway infrastructure must be kept in good functioning condition. Roadside appurtenances such as guardrails, signs, and luminaries perform major functions in the utilisation and overall safety of the highway throughout their life-cycle. As a consequence, their maintenance is very critical to maximise life of the highway and promote safe mobility. However, budget and personnel constraints make it difficult for urban cities and other local government authorities to meet highway maintenance inspection challenges. As a result, they must prioritize as well as maximise the use of manpower to keep pace with the inspection demands maintaining their highway assets. Highway assets such as guardrails, signs and luminaries become secondary priorities and are often neglected, resulting in poor maintenance and corresponding reduction in their life-expectancy. Consequently, local authorities must find the right balance between available resources and efficient use of time in order to achieve their highway maintenance objectives. In this paper, a cost minimization problem considering work-shift and overtime constraints is presented. An algorithm using Floyd's shortest path method is developed to optimize the time and paths for efficient inspection of highway assets. An illustrative example from real-life applications is presented and discussed.

Keywords: Highway infrastructure maintenance; roadside feature inventory; highway asset management; optimisation

1. Introduction

During this period of diminishing financial resources, historical under funding, increased injuries related to infrastructure, and continuing deterioration, increased rehabilitation and construction costs, many highway agencies continue to seek for more efficient ways of allocating their transport resources. With over sixty per cent of the nations' roads in substandard condition in the United States, and the significant role for commerce, economic development, security, and efficient city logistics operation, there is a dire need to extend service life of highways

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while minimizing impacts. This paper deals with the issue of highway infrastructure maintenance which is indirectly related to city logistics since for efficient city logistics operation highway infrastructure must be kept in good functioning condition.

Increasingly there has been more collaboration on behalf of stakeholders, research and design applications of effective technology and deployment of strategic plans. Many state highway agencies including Maryland State Highway Administration have engaged stakeholders in the early phase of the project development process. Improving on past procedures the agency elicits involvement of elected officials, business and private focus groups with a direct or associated interest in any planned rehabilitation or reconstruction.

Many policy initiatives are adjusted to align with procedures that deliver desired Level of Service outcomes. Additionally, the operational maintenance crews in Maryland have similar characteristics of the Capacitated Arc Routing Problem (Abdullah, 2007) with modified constraints and similar assumptions. With regard to network links, cost savings are sought in arc traversals, as they seek the highest returns on their infrastructure investments. There has been a concerted effort to use condition rating technology to separate and maintain the good elements, from those in a state of disrepair.

Other strategies include the combined investment of local communities to assist in the funding of their local projects with their financial contributions subsequent to their being informed about the status of their project and the communicated trade-offs. Current models being used now have pertinent and detailed data from resident reports, recently installed sensors, cameras, and mobile vehicles that document in-time conditions for the synchronization of their models used to produce optimal results for their analysis

Highway maintenance requires a huge commitment of capital and resources. An efficient highway maintenance program ensures safe and smooth mobility throughout the highway network and thus can be seen as indirectly related to city logistics. According to the 2002 Urban Mobility Report in 2000, congestion costs Baltimore City residents, employees, and visitors over $860 million in fuel spent and time lost in stalled traffic. Projections developed by the Baltimore Metropolitan Council indicate that congestion will steadily increase on major roadways such as I-83 and I-95 over the next 20 years (BDOT, 2003). Local, state and federal governments prioritize highway maintenance needs in order to achieve a stable and efficient transportation environment.

There are challenges in the efforts to achieve these maintenance objectives. They originate from the macro policy focus: pedestrian-transit focused policy versus vehicular movement focused policy. The former is futuristic while the later is realistic and common among state and local authorities. As a consequence, ensuring that various components of the transportation system provide acceptable levels of service, the components must work such that the overall objective to facilitate safe and smooth movement throughout the highway network is achieved. State and local authorities must therefore keep pace with corresponding maintenance demands of highway system to preserve that level of service. Maintenance of highways becomes an important priority for local and state governments. Given deteriorating transportation assets and limited resources, the priorities must further be refined to accommodate what is often considered more important: pavements, bridges and other perpetual highway assets.

Even though roadside appurtenances such as signs, guardrails and luminaries play a major role in the overall safety of the highway system, they become secondary priorities in the maintenance needs. Their maintenance is therefore, often driven by need (reactive approach) as opposed to planned (pro-active approach). To put this in perspective, the Baltimore City Department of Transportation (BDOT), notwithstanding 1600 employees, has a huge highway maintenance task which includes 1300 lane-miles of roads with 250,000 traffic and informational signs, and more. Neglect and untimely repair of these highway assets result in a short life-cycle and huge overall costs which are usually not captured during the budgetary analysis and decision making process.

Pursuing a preventive highway maintenance approach is capital intensive. However, the long term benefits outweigh the initial investment. Therefore, a sound and efficient system of inspecting these highway assets is dire and necessary to establish a baseline for repair, improvement, projection for future replacements and costs trade-offs. An efficient inspection system must be cost-effective: it must demonstrate drastic cost-savings from the current system.

The objective of this paper is to review the current inspection and inventory practices of highway appurtenances in northeast region of the United States of America using Baltimore, Maryland as a case study. The procedure for inspecting, collecting and processing resulting data, and tracking highway appurtenances are assessed. Work-shift and overtime constraints are considered in solving a cost minimization problem. An algorithm and subsequent optimisation model is developed using arc-routing principles. Illustrative examples and applications are presented and discussed.

2. Literature Review

Many research efforts in highway maintenance have concentrated on improvement of highway elements such as bridges or pavements. Golabi (see, Golabi and Shepard, 1997, Golabi et al., 1982) pioneered a shift in research focus to highway features. Since then, several contributions (Jha and Abdullah, 2008; Jha et al., 2004; Jha and Abdullah, 2006, Jha et al., 2006; Jha et al., 2008; Maji and Jha, 2007; Srensen and Faber, 2000) in the area of operations research have provided reference to analytical models that help solve highway infrastructure maintenance problems. Jha et al. (2004) made significant progress in the area of roadside feature maintenance with their work on Roadside Feature Inventory Program (RFIP) with a requirement study for Integrated Highway Maintenance Management System (IHMMS). Jha and Abdullah (2006) developed a mathematical model using the Markov Decision Process to forecast Maintenance Rehabilitation and Reconstruction (MR&R) activities over a planning horizon that could be integrated with a proposed RFIP. Abdullah (2007) focused his research work on developing a sound methodology for collecting and updating highway inventory data for the Maryland State Highway Administration (SHA) using electronic aids such as Global Positioning System (GPS) device and Geographic Information System (GIS) application.

The majority of the research work on optimisation of RFIP were done either at the state or federal level. The reason for this can be attributed to the availability of funding for such programs at the state and federal level. A recent work (Jha et al., 2004; Jha and Abdullah, 2006) focused on optimizing the life-cycle of highway appurtenances for the Maryland State Highway Administration (SHA). Jha and Abdullah (2006) assessed SHA's inventory program utilizing a Markovian model and optimisation matrices for maximizing highway life-cycle were generated using genetic algorithms.

This paper is an extension of the work done by Jha et al. (2008) that formulated a modified arc-routing problem for highway feature inspection considering work-shift and overtime limit constraints. Work-shift and overtime limit constraints are applied to the previous work by Jha and Abdullah (2006) with a focus on the highway maintenance inventory process in Baltimore, Maryland, which is used as a case study. A highway inspection optimisation model is generated to establish best practices for achieving the desired maintenance inspection goals.

2.1. Practices adopted by the city of Baltimore

Most urban cities and counties such as Baltimore City, have somewhat similar practices in how they approach inspection of highway infrastructures. They provide a strict work shift and provide operation vehicles that must be returned at the end of the work shift. Their policies generally discourage overtime. 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 (BDOT, 2003).

The inspectors effectively use 5 hours 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 (See Figure 1). Often inspection duties overlap across divisions and agencies. So that at times, inspections are duplicated by different arms of the Baltimore Department of Transportation (BDOT) or Baltimore City personnel.

Priority inspection areas include gateways. These essentially represent the priority access ways to Baltimore City. The BDOT inspector must ensure that these critical access roadways are in their best condition. The real challenge is presented when in order to accomplish this, the inspector is required to work at certain times of the day but must not exceed the work hours. For instance, an inspection of street lights must take place at night outside the regular work shift to identify which street lights are not functioning whereas signs or guardrail should probably receive a daytime visual inspection. Even though creative scheduling by BDOT ensures coverage for all the required shifts, it is sometimes unrealistic to expect normal output from odd-hour shifts with insufficient staffing.

Returning to the yard puts another impediment on data collection efforts for a meaningful inventory. There are six maintenance yards scattered all over Baltimore City (see Figure 2). Depending on the nature of inspection, the initiation point is different. However, the inspectors must abide by the same employee rules and regulations. They must all return to the yard at the end of their work shift. The work period is the same (8 hours) for all cases. Travel time to inspection sites varies from yard to yard. However, return time is fairly the same – leave one hour after beginning of shift and return one hour before end of shift. Therefore for an 8:30 a.m. to 4:30 p.m. shift, the effective work time would be 5 hours (less one-hour lunch-time) including travel time. This means that the actual time used for inspection is less than 5 hours.

Assuming the inspection times are fully utilized, there are other issues such as staffing and availability of personnel that cripple an urban cities' ability to achieve desired inventory outputs. In the case of BDOT, with the enormity of the size of assets (See Table 1) that require attention, it has not met all its staffing needs. Less than 10% of BDOT staffs perform inspections in one form or the other (BDOT, 2003). Yet budget constrains continue to demand more cuts and as a result the staff strength continue to shrink across the board.

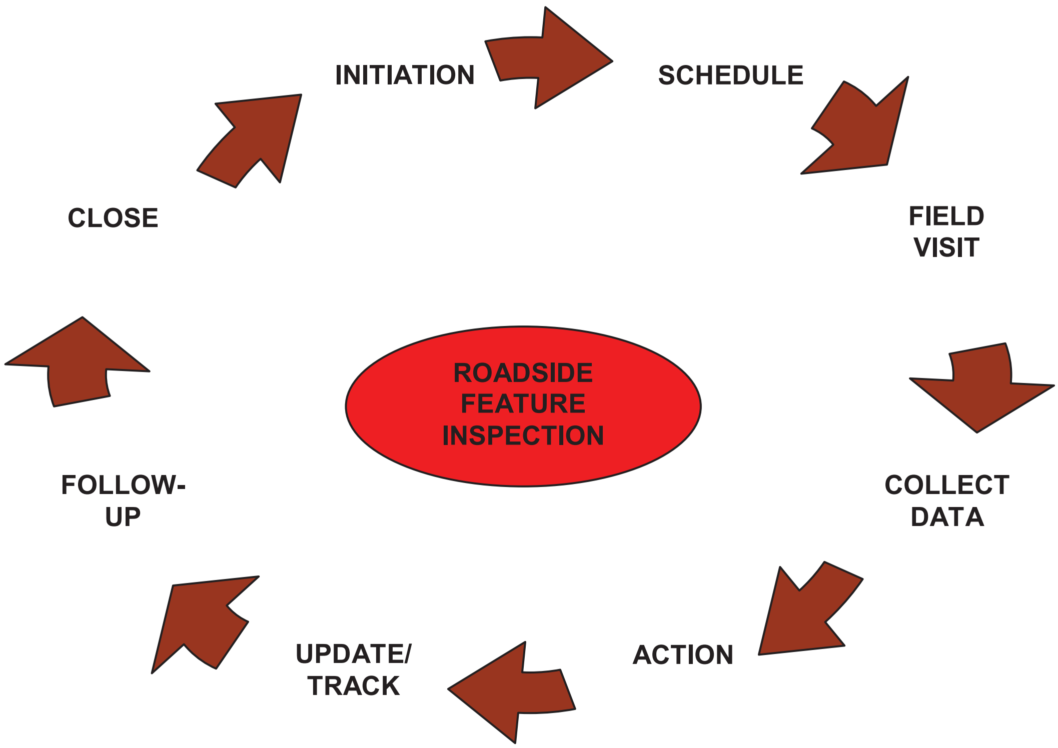

Figure 1 Baltimore city roadside feature inspection life-cycle

Table 1 Baltimore city highway assets

Infrastructure	Type	Number
Signs	Traffic and Informational	250,000 units
Signals	Intersection/Pedestrian	1300 units
Highway	Roads	2000 lane-miles
	Alleys	800 miles
	Railroads	225 miles
Structures	Bridges	300 units
Luminaries	Street Lights	80,000 units

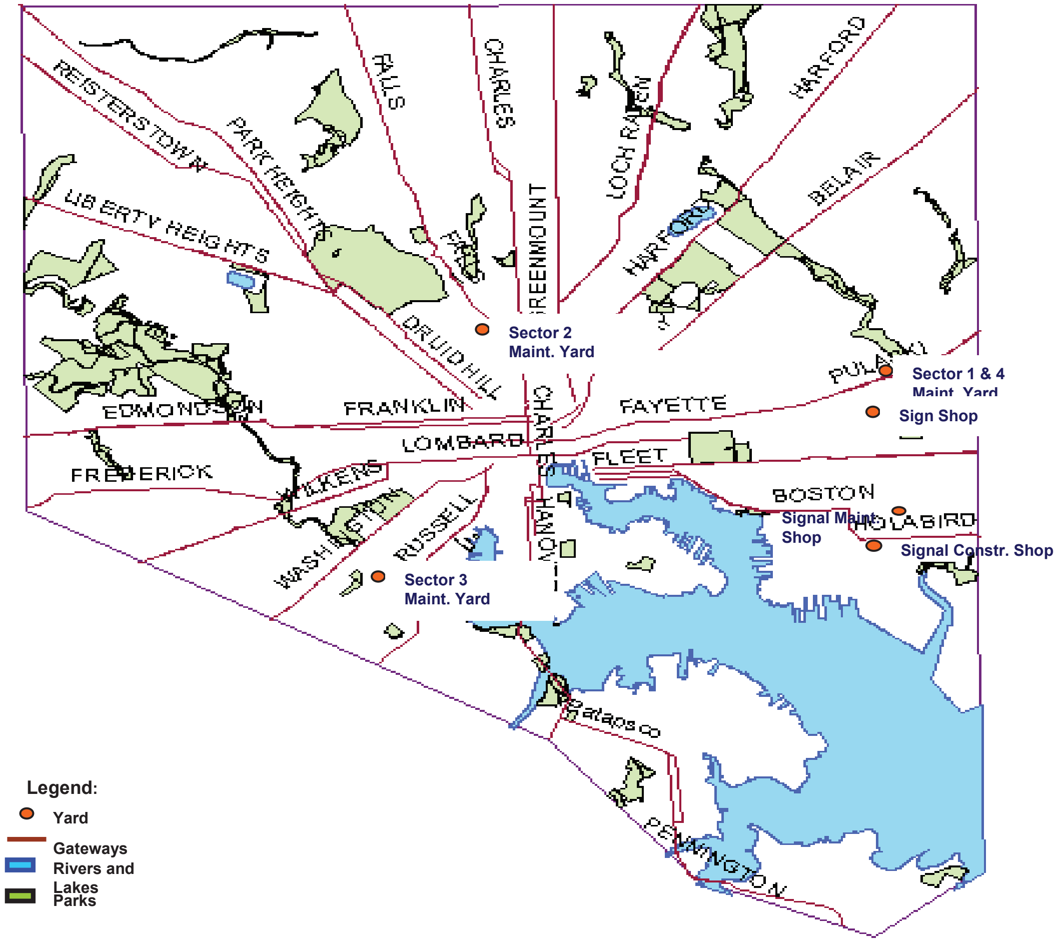

Figure 2 Baltimore city gateways and maintenance yards (Courtesy of Baltimore city DOT – Planning)

3. Methodology and Model Formulation

In this paper we will extend Jha and Abdullah's (2006) analysis for maintenance of roadside appurtenance and explore Baltimore City's approach for infrastructure maintenance. Please note that some long and short-term measures have been undertaken by Baltimore city for maintenance of roadside appurtenances. The long term approach simulates an infinite existence of pavements, i.e., different approaches can be initiated to ensure that the pavement and roadside appurtenance lasts forever. Routine maintenance is paramount to Baltimore City's strive to provide a reliable road transportation mode. Cost optimisation is the back bone of success to any agency; therefore adopting Golabi's (1997) short-term and long-term approaches will serve as a tool for developing maintenance optimisation formulations with over-time and work-shift constraints.

3.1. Model formulation

The formulation presented here for optimising the routes for roadside inspection considering work-shift and overtime limit constraints is an extension of our previous works reported (Jha and Abdullah, 2006; 2008; Jha et al., 2006; 2008). 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 the origin. Within a work-shift, *T* the time required to traverse a given arc *(i,j)* is t_{1ij}, while the time required to complete the necessary inspections along the arc is t_{2ij}. The objective function for the shortest path problem can be formulated as follows:

$$\text{Min} \quad \sum_{i,j\in A}(t_{1ij}+t_{2ij})c_{1ij}x_{ij}+\sum_{i,j\in A}(T-t_{1ij}-t_{2ij})c_{2ij}y_{2ij}x_{ij} \tag{1}$$

subject to,

$$\sum_{v\in V}x_{vi}-\sum_{v\in V}x_{iv}=0,\ \forall v\in V \tag{2}$$

$$T\geq(t_{1ij}+t_{2ij})\ \ \forall(i,j)\in A \tag{3}$$

$$T,t_{1ij},t_{2ij},c_{1ij},c_{2ij},x_{ij}\geq 0 \tag{4}$$

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
x_{ij} : Number of times arc $(i,j)\in A$ is traversed

$$y_{1ij}=\begin{Bmatrix}1 \text{ if arc } (i,j) \text{is traversed or inspected}\\ 0 \text{ otherwise}\end{Bmatrix}$$

$$y_{2ij}=\begin{Bmatrix}1 \text{ if } T> \text{a specified regular - time work - shift (usually 8 hrs.)}\\ 0 \text{ otherwise}\end{Bmatrix}$$

The objective function expressed in equation (1) minimizes total route cost to travel and complete the necessary inspections. Equation (2) ensures route, eq. (3) ensures that the available work-shift is equal to or more than total time to travel and inspect, and eq. (4) is the non-negativity constraint. Since c_{2ij} is the unit cost for completing the travel and inspection in overtime, which is higher than c_{1ij}, the model will automatically attempt to minimize the required overtime.

4. Solution Algorithm

The above optimisation formulation can be solved using a Floyd Algorithm. A short description of the algorithm is provided below:

Given a graph G which has nodes (n_i) and links ($l_{i\text{-}j}$), shortest distance and path between any two nodes can be obtained using the Floyd's Algorithm. Let there be *n* nodes in a graph. Let $d_{i\text{-}j}$ be the distance from *i* to *j* if the link $l_{i\text{-}j}$ exists else it value is infinite. Then pseudo code for the algorithm is given as:

```
For k=1 to n
    For  i = 1 to n
        For j = 1 to n
```

$d_{i\text{-}j} = min(d_{i\text{-}j}, d_{i\text{-}k}+d_{k\text{-}j})$

End

End

End

$\forall \quad i, j, k = 1,2,3..n \in G$

5. A Numerical Example

The above algorithm is employed to obtain the optimal inspection routes for the network shown in Figure 3. The travel and inspection times for the example network are shown in Table 2. The unit regular-time cost is assumed to be $16/hr and the unit overtime cost is assumed to be $24/hr for each inspector. A crew of 4 is assumed to carry the inspection and their pay rate is assumed to be uniform for simplicity. Thus, the unit regular-time and overt-time crew costs are $64 and $96, respectively.

The obtained optimal routes and costs are given below:

Route 1 : 25,18,22,14,23,26,27,29,31,28,20,19,21,30 (TT+IT = 472 min), all completed in regular time in 59 working days of 8 hour work-shift.

Route 2 : 32,24,13,12,6,7,8,1,2,3 (TT+IT = 457 min), completed in 57 regular-time days and 1 over-time hour.

Route 3 : 33, 5,4,11,10,17,15,16,9 ((TT+IT = 356 min)), completed in 44 regular-time days and 4 over-time hours.

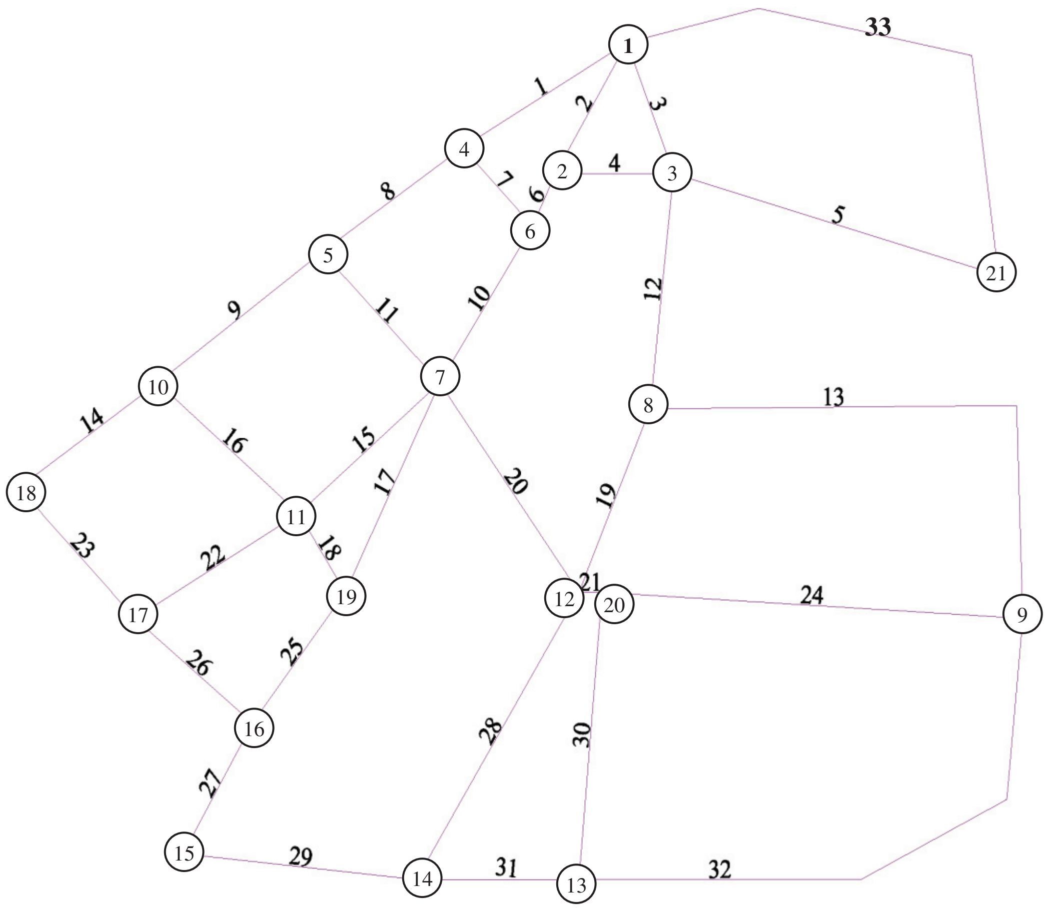

Figure 3.Example highway network

Table 2 Travel and inspection times for the example network

ARC	Travel Time, TT (min)	Inspection Time, IT (min)	ARC	Travel Time, TT (min)	Inspection Time, IT (min)
1	10	22	18	4	20
2	7	12	19	9	15
3	6	12	20	12	31
4	6	11	21	1	10
5	12	21	22	10	37
6	3	10	23	8	21
7	5	13	24	22	51
8	9	16	25	8	18
9	10	18	26	8	14
10	9	15	27	7	25
11	9	17	28	16	53
12	11	21	29	12	19
13	29	56	30	13	16
14	9	14	31	8	17
15	9	14	32	31	68
16	9	18	33	34	76
17	11	25			

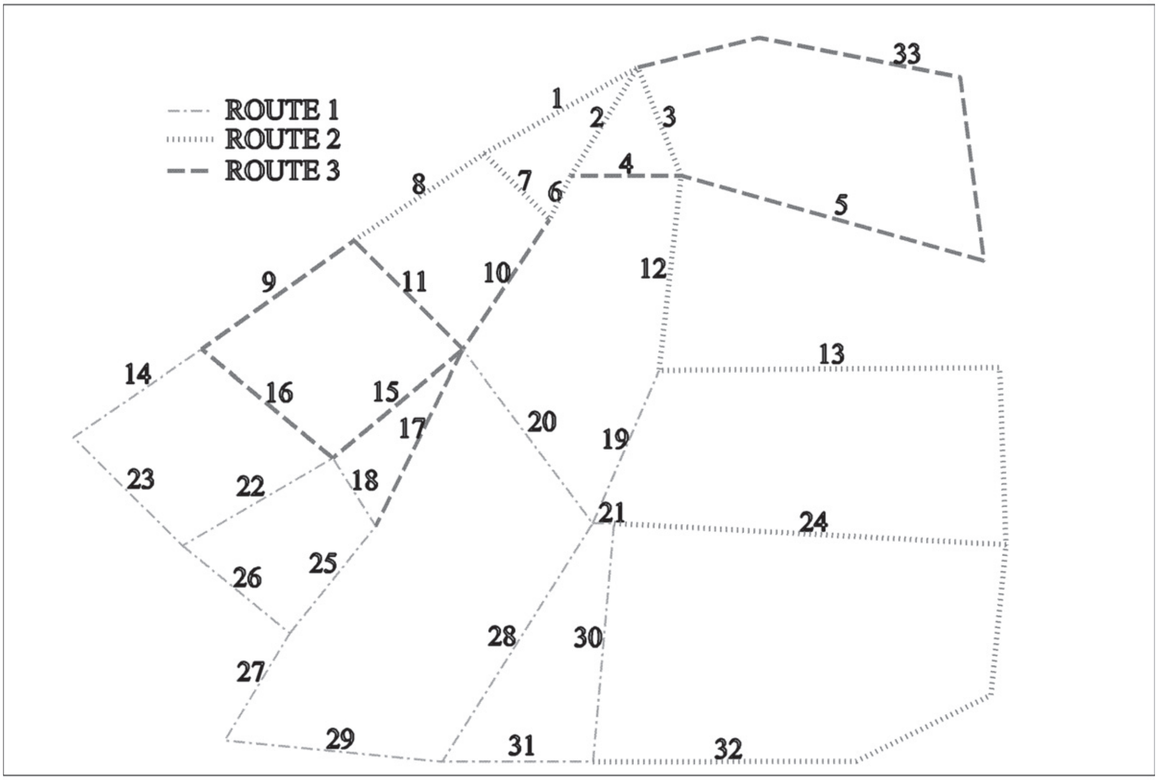

Figure 4 Optimal results for the example network using Floyds' algorithm

6. Conclusions and Future Works

The optimisation model developed in this research work may not be useful in the short term. The true value can be determined when certain initiatives are in place and functional. However, there is opportunity to improve on current maintenance inspection practices in Baltimore City, Maryland. To establish the baseline for current conditions of all highway assets, a robust inventory program must be implemented. Government authorities must show commitment to top-down approach to highway maintenance by adequately accounting and funding all aspects of highway maintenance including roadside appurtenances. The challenges of increasing staff levels in local governments such as Baltimore City are both a policy decision and a budget question. Decreased staff sizes and decreased budget levels appear to be a threat to maintaining a viable Roadside Feature Inventory Program (RFIP) at the local DOT level. A solution to the problem of declining staff levels and increasing data needs for a meaningful RFIP is a careful automation of data collection and input using modern technologies. While the desire continues to grow to consolidate collection efforts for roadside feature inventory data within a single Asset Management Plan (AMP), it will be years before the true impact of this optimisation model in terms of cost saving would be realized. The analytical model needs to be further refined to perform extensive sensitivity analysis using varying network size.

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