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Road maintenance planning using network flow modelling

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This paper presents a road maintenance planning model that can be used to balance out maintenance cost and road user cost, since performing road maintenance at night can be convenient for road users but costly for highway agency. Based on the platform of the network traffic flow modelling, the traffic through the worksite and its adjacent road links is evaluated. Thus, maintenance arrangements at a worksite can be optimized considering the overall network performance. In addition, genetic algorithms are used for maintenance planning in order to find the best maintenance arrangements for the worksites. The key variables in the optimization model involve the starting time of maintenance works during the day, their duration, the duration of the break during the maintenance work and traffic signal controls at the worksite.

Keywords: maintenance planning; network flow modelling; genetic algorithms.

1. Introduction

Maintenance and rehabilitation (M&R) activities on highways usually disrupt traffic flow and can increase safety hazards for road users and workers. Therefore, M&R activities can be expensive not only in terms of the highway agency cost but also in terms of the user cost. Owing to traffic delays, the user cost frequently exceeds the maintenance cost by far. Efficient scheduling of M&R works may greatly reduce user cost. Such scheduling can be achieved, for example, by finding the most convenient starting time of maintenance works and setting the traffic controls at the worksite appropriately. In order to minimize road user costs due to maintenance, highways agencies usually restrict maintenance activities to off-peak periods. Using a nighttime maintenance shift is the best option in terms of achieving the minimum traffic congestion. However, nighttime maintenance operations have a health safety risk due to road workers, and their cost to highways agencies is also high. If the additional road user costs due to maintenance are acceptable, daytime maintenance operations are preferable to highways agencies, since the safety of road workers is ensured and agency costs minimized. As a consequence, it is of vital importance to be able to find a balance between road user costs and agency costs.

A 'worksite' can be defined as an area on a multi-lane highway, where one or more lanes are closed for maintenance (Chien *et al.*, 2002). Since the scheduling of M&R activities is of major concern of the highways agency and local authorities, many studies have been performed in this area. Some studies have focused on the optimization of the worksite length considering its impact on agency cost and road user cost. For example, a mathematical model was proposed by Schonfeld & Chien (1999) to optimize the worksite length and related traffic controls on two-lane and four-lane highways, where one lane closure was implemented. The underlying assumption for these studies was that the traffic flow heading to the worksite was constant.

Some studies have been devoted to the optimization of the worksite schedule, which resulted in the minimal total cost, consisting of the agency cost and road user cost. The mathematical approach developed by Schonfeld & Chien (1999) was also used to optimize the worksite schedule (Chien *et al.*, 2002). Considering different lane closure situations, Fwa *et al.* (1994) optimized the worksite schedule and minimized traffic delays subject to constraints of maintenance operational requirements using genetic algorithms (GAs). Jiang & Adeli (2003) proposed a Boltzmann-simulated annealing neural network to optimize the worksite arrangements, i.e. the worksite length and the starting time of the work.

Owing to significant traffic delays because of roadworks, drivers may change their route through the network and avoid congested road sections. The methodology developed by Chien & Schonfeld (2001) was used to jointly optimize the worksite length and the traffic diversion fraction due to traffic condition on the alternative routes close to the worksite using GAs by Chien & Schonfeld (2005). Afterwards, an analytical model was constructed to optimize the worksite length, the maintenance schedule and the traffic diversion fraction, while considering time-dependent traffic, maintenance cost and production rates of maintenance teams. In addition, the capacity and speed controls on worksites were investigated, considering road users and maintenance workers safety (Memmott & Dudek, 1984; Richards & Dudek, 1986; Shepard and Cottrell Jr, 1986; Krammes & Lopez, 1994).

In order to overcome the huge computational effort incurred by maintenance arrangement problem GAs are commonly deployed as the optimization tool (Chan *et al*., 1994; Fwa *et al*., 1998; Ferreira *et al*., 2002; Abaza & Ashur, 2009). GAs can be applied to the M&R optimization problem because of their robust search capabilities that overcome the combinatorial explosion of large-size optimization problems and are based on the survival-of-the-fittest concept of Darwinian evolution (Holand, 1975). The major barrier of the optimization problem is that the solution space grows exponentially with the size of the problem, so the conventional optimization approach can be inefficient to find the optimal solution. However, GAs, which incorporate a set of initial solutions and generate new and better solutions according to the probabilistic rules, can be more effective and the likelihood of achieving the optimal solution is increasing (Morcous & Lounis, 2005).

The traffic flow modelling techniques, discussed above, mainly focus on traffic delays occurring at the worksite, while traffic conditions in the links adjacent to the worksite are not considered. As the traffic flows on each link in the network are dependent on each other, it is important to optimize the worksite arrangements by considering their impact on the overall network performance. In this paper, network traffic flow modelling (NTFM) (Yang *et al.*, 2014) is enhanced to model the effects of maintenance works on the network while minimizing the detriment to the road users. Comparing with the existing traffic models, NTFM is capable of predicting the network performance and can be used to forecast the traffic flow rates and queue dynamics on road links in the overall highway network. In addition, a roadwork node sub-model is introduced, which is then applied to evaluate the effect of maintenance activities on network level performance, making it a suitable platform for evaluating travel delays. By comparing the traffic outputs and queues in the network under alternative maintenance strategies, the best way of maintaining the serviceability of highways can be achieved. The GA approach is used to search for the best starting time of maintenance works and the phases of traffic signals for the chosen strategy, when their effects on the network are evaluated using the NTFM.

The outline of this paper is as follows: Section 2 presents the general rules for NTFM and the junction types modelled, including a roadwork node. Section 3 describes the features of the case study network on Loughborough–Nottingham highway network, its calibration and its performance under different traffic conditions throughout a day. Section 4 presents the findings based on the numerical performance of the network under different maintenance scenarios, and states that it identifies the strategy on the trade-off between maintenance costs and road user costs. Section 5 depicts the optimization of M&R strategy for the example network, and proposes an optimal schedule that is suitable for balancing out maintenance costs and road user costs.

2. Proposed methodology

In this paper, the objective function is the total cost, which contains the agency cost and road user cost, and it is used to optimize the maintenance schedule and traffic controls at worksites. First of all, a number of different maintenance strategies are considered and a strategy which is the best for balancing out the road user cost and the agency cost is identified. Then an optimization routine is implemented in order to find optimal values of maintenance parameters, such as the starting time of work and traffic controls, for the chosen strategy.

2.1 *Cost calculation*

The total cost function is the sum of the agency cost and the road user cost. Agency cost is derived from the maintenance cost directly, while road user cost is calculated in terms of travel delays occurred on the network.

2.1.1 *Agency cost* The agency cost is the sum of the maintenance cost spent on each worksite. The maintenance cost incurred on worksite i, C_i, is formulated as

$$C_i = c_0 + c_{k,r} \times l_i \tag{1}$$

where c_0 is the fixed cost for setting up a worksite, £'1000s, assume $c_0 = 1$; k is the maintenance action implemented on worksite i; r is the road type of worksite i; $c_{k,r}$ is the cost of maintenance action k associated with road type r, £'000s, per lane kilometre; l_i is the length of worksite i, lane kilometre.

The corresponding maintenance duration spent on worksite i, D_i, is represented by

$$D_i = d_0 + d_{k,r} \times l_i \tag{2}$$

where d_0 is the fixed set up time for a worksite, hours, assume $d_0 = 1$; $d_{k,r}$ is the time required for maintenance action k associated with the road type r, hours, per lane kilometre.

The cost and duration for each type of maintenance action and type of road is described in Table 1 (DfT, 1997).

2.1.2 *Road user cost* Road user cost is determined as the total travel duration spent on the highway network multiplied by the monetary value of time. The road user cost spent on road section j at time k, $T_j(k)$, is computed as

$$T_j(k) = t_j(k) \times v \tag{3}$$

where $t_j(k)$ is the total travel duration spent on road section j at time k, hours; v is the time value for road user, £/h, the market price value of time for an average vehicle is £15.38 per hour, 2012 prices and values, published by DfT (2011).

The total travel duration, $t_j(k)$, is the sum of the journey time spent on section j, $t_{j,J}(k)$, and the travel delay which takes place at the junction downstream of section$j$, $t_{j,D}(k)$, described as

$$t_j(k) = t_{j,J}(k) + t_{j,D}(k) \tag{4}$$

TABLE 1 *Maintenance duration and cost for each combination of maintenance action and road type (per lane kilometre)*

	M&R	Single carriageway (S2)		Dual 2 lane carriageway (D2AP)		Dual 3 lane Motorway(D3M)	
ID	Type	Duration (h)	Cost (£'000s)	Duration (h)	Cost (£'000s)	Duration (h)	Cost (£'000s)
0	Do nothing	0	0	0	0	0	0
1	Patching	24	15	18	15	16	13.33
2	Surface dressing	48	20	30	20	24	16.67
3	Resurfacing	96	60	84	82.5	80	90
4	Overlay	192	95	138	122.5	132	135

Note that costs are in expressed in £'000s according to 2012 prices.

The total travel duration spent on the network at time k,$t(k)$, is evaluated as

$$t(k) = \sum_{j=1}^{M} t_{j,J}(k) + \sum_{i=1}^{N} t_{i,D}(k) \tag{5}$$

where $t_{j,J}(k)$ is the journey time spent by road users on link j at time k, which is calculated considering the travel time for the non-disturbed traffic that pass through the link without delays, the time spent on queue formation and the time spent on queue dissipation; M is the number of links on the network; $t_{i,D}(k)$ is the travel delay time spent by road users at junction i in time k, which is expressed as the function of the queue length, $q_a(t)$

$$t_{i,D}(k) = \sum_{a=1}^{A} \int_{k-1}^{k} q_a(t)\,\mathrm{d}t \tag{6}$$

where $q_a(t)$ is the length of the queue on arm a to junction i in time t; A is the number of arms at junction i. Note that the relationship between the queue and time is assumed to be linear; N is the number of junctions on the network.

2.2 *Maintenance modelling using NTFM*

The NTFM model considers different types of maintenance works, i.e. roadworks on a single carriageway, on a dual carriageway and on a three lane dual carriageway. The model of maintenance work is introduced to NTFM by using a roadwork node. Roadwork node is used to define the length of the worksite, and the number of lanes in maintenance. The closure situation for each road type is described below.

2.2.1 *Single carriageway* For a single carriageway road, a shuttle working is employed to facilitate the traffic flows from opposing directions. As for the average speed through the road link with worksite, it has been assumed that the travel speeds for light vehicles and heavy vehicles through the worksite are 43.9 and 38.2 km/h, respectively (DfT, 2004). In this paper, the average speed at the worksite is selected as the travel speed for heavy vehicles.

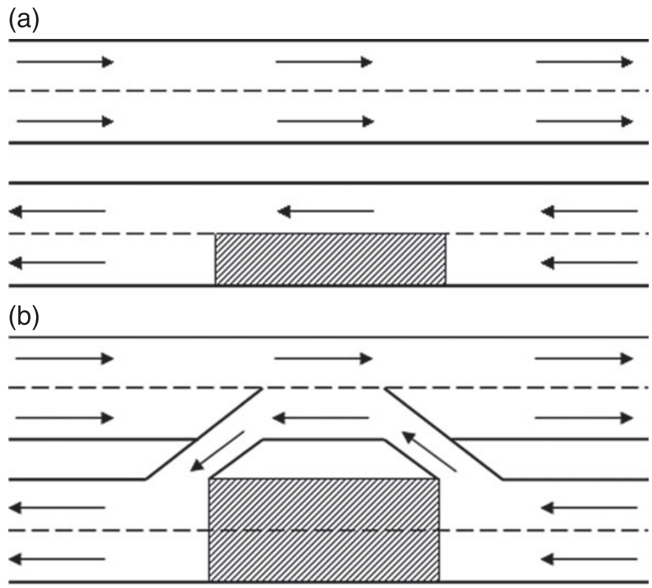

FIG. 1. Dual 2 lane carriageway road with work: (a) one lane closure; (b) two lane closure and crossover.

2.2.2 *Dual 2 lane carriageway* As for a Dual 2 lane carriageway, a one lane closure or a two lane closure can be used in maintenance, as shown in Fig. 1.

For a one lane closure, only one of the service lanes in one direction is closed due to maintenance. Therefore, in this case maintenance has no impact on the traffic flow in the opposite direction. For a two lane closure, both of the service lanes in one direction are closed, and the road becomes effectively a single carriageway. At the direction with one service lane, the average speed is reduced from 112 to 80 km/h.

One lane closure: Provided that one of the service lanes in one direction is closed due to maintenance, as shown in Fig. 1(a), the flow capacity on the closed lane becomes zero, and the flow capacity on the other lane in this direction decreases due to speed limits. According to the delay modelling in QUADRO (DfT, 2004), the overall worksite capacity on the road with maintenance would be reduced to

$$C_{D,1} = 0.85 \times C_{n,i} \tag{7}$$

where $C_{n,i}$ is the normal capacity for a lane that belongs to road class i, pcu/h, pcu stands for passenger car unit; $C_{D,1}$ is the reduced capacity, pcu/h.

Two lane closure: For a two lane closure, the number of service lanes in each direction is reduced to one. The resulting site capacities for both directions are calculated by Equation (7).

2.2.3 *Dual 3 lane motorway* In this case, three options are possible, a one lane closure, a two lane closure, a full carriageway closure with crossover. For a one lane closure option, the average speed at the road link with worksite remains 112 km/h. When a two lane closure is implemented, the average speed is decreased to 80 km/h.

If N lanes are in service through the worksite during maintenance, the worksite capacity would be formulated as shown in Equation (8).

$$C_{D,1} = 0.85 \times N \times C_{n,i} \quad (8)$$

2.3 *Modelling assumptions*

Several assumptions have been made in this study:

(1) For a typical day, 7:00–23:00 is defined as daytime, while the rest is nighttime.

(2) The maintenance work rates for maintenance workers during the daytime and nighttime are the same.

(3) The unit cost at the nighttime is double that of in the daytime. The daytime maintenance cost is shown in Table 1.

(4) The minimum duration for a single maintenance work slot is 2 h. The maximum gap between two slots is set to be 2 h.

(5) It is assumed that only two time slots are possible during a day, i.e. only one maintenance break is possible.

(6) Once the maintenance activity completed, the road condition returns to normal.

(7) If there is a gap between two slots, the maintenance set up cost and time need to be taken into account, as described in Equations (1) and (2), respectively.

2.4 *GA implementation*

GAs imitate the natural process of biological evolution and can be more efficient than iterative method and linear programming, since the probability of reaching the optimal solution is greater than using traditional optimization approaches. The process with each generation begins by generating an initial pool of genotypes to represent a set of feasible solutions, and then each individual within the initial pool is evaluated using the objective function and ranked in terms of its fitness, which is expressed as the value of the objective function. With the aid of genetic operators, i.e. reproduction, crossover and mutation, each genotype is allowed to create a certain number of offspring depending on its fitness. With respect to the values of the objective function, relatively better solutions would be retained, while the rest would be deleted. As a consequence, a new parent pool is formed by selecting the desired number of offspring. The genetic selection process, solution-pool selection process and offspring generation are repeated until the result reaches convergence or a maximum iteration set by the user is met.

2.4.1 *Decision variables*

In terms of the assumptions listed in Section 2.3, the decision variables for each road section include start time of maintenance, T_s, maintenance duration 1, $D_{m,1}$, maintenance break, B_m and maintenance duration 2, $D_{m,2}$, for each working day. When the investigated road link belongs to a single carriageway, the green splits for the opposing directions during maintenance are also optimized.

The constraints for these variables are formulated as

$$T_{s,e} \leqslant T_s \leqslant T_{s,l} \tag{9a}$$

$$D_{m,\min} \leqslant D_{m,1} \leqslant D_{m,\max} \tag{9b}$$

$$D_{m,\min} \leqslant D_{m,2} \leqslant D_{m,\max} \tag{9c}$$

$$B_{m,\min} \leqslant B_m \leqslant B_{m,\max} \tag{9d}$$

where $T_{s,e}$ and$T_{s,l}$ represent the earliest and the latest starting time of maintenance.

The first constraint in Equation 9(a) restricts the start time of maintenance action for each day. Equations (9b) and (9c) limit the duration for each maintenance time slot. The fourth constraint in (9d) is the threshold of the maintenance break, which aims to avoid peak time. As for single carriageway, more constraints are considered:

$$S_{g,\min} \leqslant S_{g,1} \leqslant S_{g,\max} \tag{9e}$$

$$S_{g,\min} \leqslant S_{g,2} \leqslant S_{g,\max} \tag{9f}$$

These two constraints in (9e) and (9f) are used to define the range of green phases for each direction on the single carriageway during maintenance. $S_{g,i}$ represents the green split for one direction during the maintenance duration i, the green split for the other direction is evaluated as $(100 - S_{g,i})$%-*amber phase*, where *amber phase* is defined as 10% of the cycle. Other constraints can be added according to the requirements of highways agencies, i.e. the restriction of the number of major maintenance actions. In this paper, a single-objective GA is utilized to optimize the decision variables for road sections on a network.

2.4.2 *Objective function* Based on the variables listed in Section 2.4.1, the number of working days for each road link under maintenance is calculated as

$$D_{\text{work}} = \frac{D_{\text{M}}}{D_{m,1} - 1 + D_{m,2} - 1} \tag{10}$$

where D_{M} represents the required maintenance duration. $D_{m,1} - 1$ is the time devoted to pavement maintenance by subtracting the maintenance set up time from the maintenance duration 1. *wd* is rounded to the closest integer number when it is a decimal number. As a result, the total cost spent on the network during the whole maintenance period is evaluated as

$$C_T = D_{\text{work}} \times C[T_s, D_{m,1}, B_m, D_{m,2}] \tag{11}$$

where $C[T_s, D_{m,1}, B_m, D_{m,2}]$ represents the total cost spent at each working day under the specific maintenance arrangements T_s, $D_{m,1}$, B_m and $D_{m,2}$, which is calculated as the total travel duration multiplied by the value of time. In addition, green splits, $S_{g,1}$ and $S_{g,2}$ are taken into account when single carriageway is studied. The maintenance arrangement with the least C_T is recognized as the optimal one with the objective of minimizing road user cost. C_T is calculated using the NTFM. The evaluation of maintenance arrangements for road sections on an example network is illustrated in the following section.

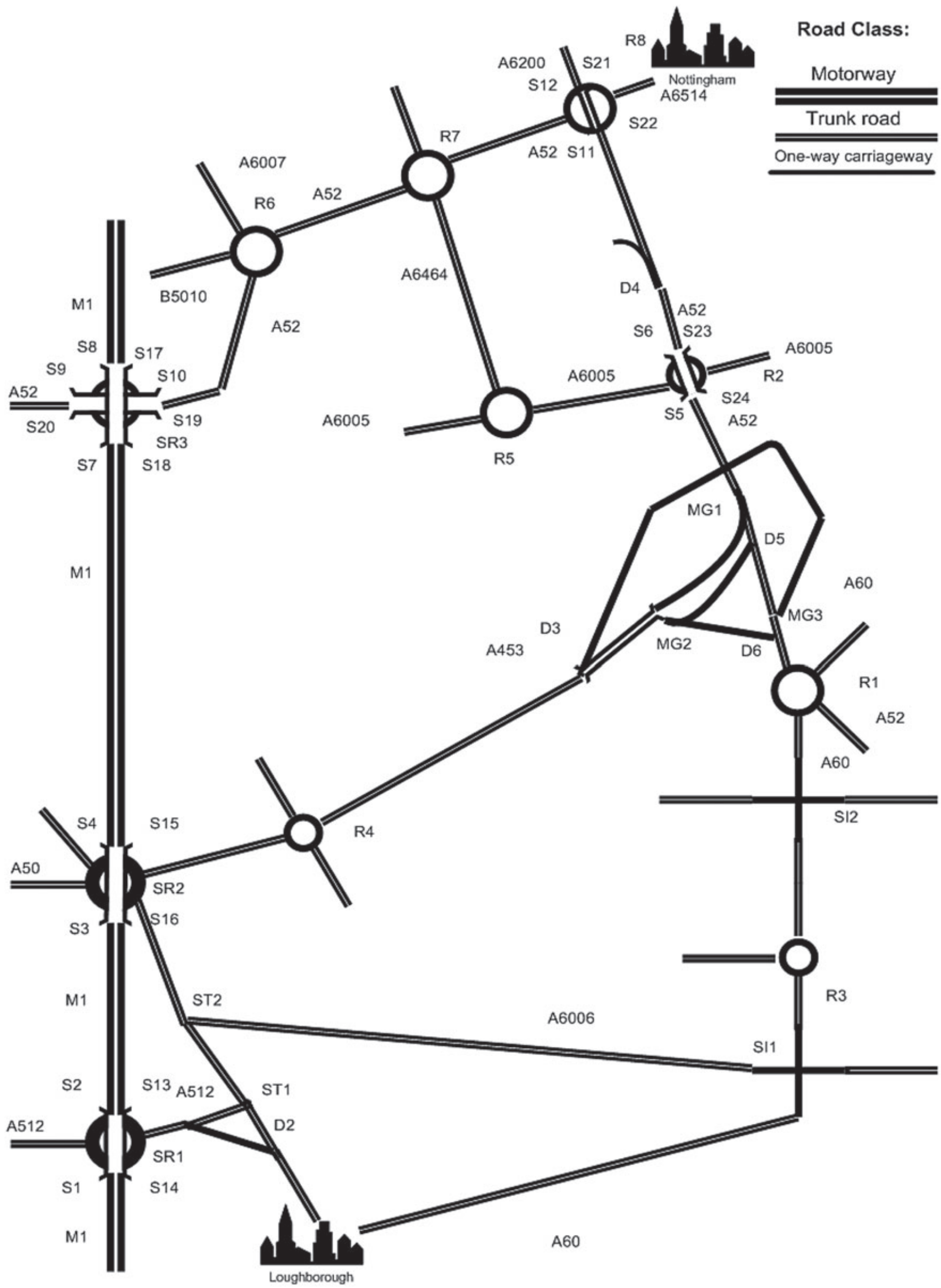

FIG. 2. Loughborough–Nottingham modelled highway network.

TABLE 2 *Queue length for the congested links on the network under normal conditions*

	R6		R7	R1	SI2			
Link	B5010	A6007	Residential area	SI2-R1	Ruddington	R3-SI2	Westbound arm	Total queue (pcu)
8:00	320	0	264	89	0	0	0	673
9:00	620	0	0	125	17	39	3	804
10:00	0	162	0	125	44	102	8	441
11:00	0	0	0	0	0	0	0	0
17:00	240	0	231	0	0	0	0	471
18:00	540	0	506	0	0	0	0	1,046
19:00	0	143	0	0	0	0	0	143
20:00	0	0	0	0	0	0	0	0

TABLE 3 *Travel delay for the congested links on the network under normal conditions*

	R6		R7	R1	SI2			
Link	B5010	A6007	Residential area	SI2-R1	Ruddington	R3-SI2	Westbound arm	Total delay (h)
8:00	160	0	132	44.5	0	0	0	336.5
9:00	470	0	30.1	107	8.5	19.5	1.5	636.6
10:00	165.6	81	0	125	30.5	70.6	5.5	478.2
11:00	0	10.4	0	4.8	0.8	1.14	0.06	17.2
17:00	120	0	115.5	0	0	0	0	235.5
18:00	390	0	368.5	0	0	0	0	758.5
19:00	135	71.5	108.5	0	0	0	0	315.0
20:00	0	8.01	0	0	0	0	0	8.01

3. Example network

To investigate the impact of maintenance arrangements on road users and illustrate the methodology, the Loughborough–Nottingham highway network is studied which is composed of 47 junctions and 51 road links, illustrated in Fig. 2.

According to the simulation results obtained by NTFM, the travel delay taken place on the network under normal conditions is obtained as 2,785.5 h, which is contributed from the congestion links on the network throughout the day. The queue length for each congested link through the day is shown in Table 2.

Travel delays spent on the congested links are calculated in terms of Equation (6), described in Table 3. Afterwards, the total travel delay is transformed to road user cost by multiplying time value, £15.38, obtained as £42,840.8.

4. Maintenance effects on example network

The maintenance on road links *MG2-R4* (a dual carriageway) and *SR2-R4* (a single carriageway) are studied to analyse the influence of maintenance arrangements on agency costs and road user costs.

TABLE 4 *Maintenance cost and duration for road link MG2-R4*

Maintenance action	1
Length (km)	2.8
Duration (h)	102
Cost (£'000s)	85

4.1 *Possible maintenance arrangements on dual carriageway (MG2-R4)*

Assume that the road link *MG2-R4* is undergoing a repair, implementing patching. The length of link *MG2-R4* is 1.75 miles, and one lane closure is applied to conduct maintenance activities, as defined in Fig. 1(a). Three possible maintenance schedules are chosen: the first arrangement (4.1.1) is to start maintenance at 7:00 and carry it out during daytime only until it is finished; the second arrangement (4.1.2) is to perform maintenance activities off-peak, i.e. 11:00–16:00 and 19:00–23:00; the third arrangement (4.1.3) is to perform maintenance at nighttime only, i.e. from 23:00 till 7:00.

4.1.1 *Maintenance arrangement 1* The duration and cost of patching road link *MG2-R4* is calculated using data in Table 1 and Fig. 2, i.e. the duration for maintenance action 1 is calculated as, $D_1 = 1 + 1.75 \times 1.6 \times 2 \times 18 = 102$. Note that road link *MG2-R4* is a two lane carriageway. The agency cost is calculated using Equation (1), $C_1 = 1 + 1.75 \times 1.6 \times 2 \times 15 = 85$. The length of road link is calculated as 2.8 km by multiplying 1.6, which aims to transfer mile to kilometre (Table 4).

In order to calculate the road user cost when road link *MG2-R4* is undergoing maintenance, the NTFM model is used. In this maintenance arrangement, it takes 4 days and 5 h to complete the job. The traffic conditions on the road link *MG2-R4* through 1 day under this maintenance arrangement are shown in Table 5.

Table 5 indicates that road link *MG2-R4* experienced severe traffic congestion when the inflow is a lot higher than the outflow. Owing to maintenance, the flow capacity of *MG2-R4* is decreased from 3,600 to 1,530 pcu/h using Equation (7). Thus, the inflows at daytime are greater than the flow capacity. Also it is assumed that the link capacitance of *MG2-R4* is a 457 pcu. In the NTFM, when the number of delayed vehicles exceeds the capacity, the remainder of the vehicles are propagated back to their source links to show the effects on the rest of the network.

As for the network under maintenance 1, the travel delay for each of the first 4 days is achieved as 89,617.65 h, which corresponds to £1,378,319.5. While for the fifth day, one lane closure is applied during 7:00 and 12:00, the resulting travel delay is obtained as 15,685.6 h that costs £241,244.5. The additional road user cost for maintenance arrangement 1 is computed as, $uc_{ad,1} = 1378319.5 \times 4 + 241244.5 - 42840.8 \times 5 = 5540318.5$, where $uc_{ad,n}$ is the additional road user cost under maintenance arrangement n, which is evaluated by subtracting the road user cost under the normal condition from that under maintenance arrangement n during the maintenance period.

4.1.2 *Maintenance arrangement 2* For maintenance arrangement 2, the maintenance duration for each day is 9 h, which requires 15 working days with the consideration of maintenance set up time according to Equation (2). In the first 14 working days, maintenance activities are performed at 11:00–16:00 and 19:00–23:00. As for the last working day, maintenance slot falls to 11:00–15:00.

TABLE 5 *Traffic conditions on road link MG2-R4 under maintenance 1*

Time	Inflow (pcu/h)	Flow capacity (pcu/h)	Outflow (pcu/h)	Queue (pcu)	Queue propagation (pcu)
7:00	2,033	1,530	1,530	457	46
8:00	2,603	1,530	1,530	457	1,073
9:00	3,123	1,530	1,530	457	1,593
10:00	3,785	1,530	1,530	457	2,255
11:00	3,900	1,530	1,530	457	2,370
12:00	4,116	1,530	1,530	457	2,586
13:00	3,955	1,530	1,530	457	2,425
14:00	4,030	1,530	1,530	457	2,500
15:00	4,234	1,530	1,530	457	2,704
16:00	4,103	1,530	1,530	457	2,573
17:00	4,235	1,530	1,530	457	2,705
18:00	4,441	1,530	1,530	457	2,911
19:00	4,157	1,530	1,530	457	2,627
20:00	3,941	1,530	1,530	457	2,411
21:00	3,721	1,530	1,530	457	2,191
22:00	3,598	1,530	1,530	457	2,068
23:00	2,750	1,530	1,530	457	1,220
24:00	1,251	1,530	1,530	178	0
1:00	31	1,530	209	0	0
2:00–7:00	31	1,530	31	0	0

The duration for maintenance action 1 under maintenance arrangement 2 is calculated as $D_2 = 29 \times 1 + 1.75 \times 1.6 \times 2 \times 18 = 130$, and agency cost is calculated using Equation (1), $C_2 = 29 \times 1 + 1.75 \times 1.6 \times 2 \times 15 = 113$, where 29 represents the number of time slots during the whole work process.

For each of the first 14 working days, the travel delay and cost to road users are calculated as 7,768.54 h and £119,480 by using NTFM. For the 15th working day, the travel delay and road user cost are obtained as 5,098 h and £78,407.6. In terms of the method proposed in Section 4.1.1, the additional travel delay and cost to road users on the network under maintenance arrangement 2 are evaluated as 72,075 h and £1,108,516, shown as $uc_{ad,2} = 119480 \times 14 + 78407.6 - 42840.8 \times 15 = 1108516$.

4.1.3 *Maintenance arrangement 3* For maintenance arrangement 3, nighttime operation is applied. The maintenance work starts from 23:00 to 7:00 on the next day, which requires 15 days to complete the project in terms of Equation (7). For the first 14 days, the road section is maintained at 23:00–7:00. While for the last day, maintenance work is performed at 23:00–3:00.

The duration for maintenance action 1 under maintenance arrangement 3 is calculated as $D_3 = 15 \times 1 + 1.75 \times 1.6 \times 2 \times 18 = 99$, and agency cost is calculated using Equation (1), $C_3 = 15 \times 1 + (1.75 \times 1.6 \times 2 \times 15) \times 2 = 183$, where 15 represents the number of time slots during the whole work process, and the maintenance at nighttime is doubled.

Afterwards, NTFM is applied to model the traffic characteristics on the network under maintenance arrangement 3.

TABLE 6 *Maintenance cost and road user cost spent on the network under various maintenance arrangements when maintenance action 1 is performed*

Maintenance arrangement	1	2	3
Additional travel delay (h)	360,228.75	72,075	0
Maintenance cost (£'000s)	85	113	183
Additional road user cost (£'000s)	5,540	1,109	0
Total cost (£'000s)	5,625	1,222	183

The results show that the same traffic conditions are experienced on road link *MG2-R4* as that on the network under normal conditions. This is because maintenance activities are performed at nighttime when limited traffic existed on the network.

4.1.4 *Discussion of the three maintenance arrangements* The results obtained under the three maintenance arrangements are compared in Table 6.

In Table 6, total cost is evaluated as the sum of maintenance cost and additional road user cost. It can be observed from Table 6 that maintenance arrangement 1 resulted in the most additional road user cost, since maintenance was carried out at daytime as well as nighttime. However, it required the least funding from highway agencies due to no breaks in the schedule and a small amount of nighttime hours. As for the maintenance arrangement 2, the road was only maintained off-peak, which caused less disruption to road users than in maintenance arrangement 1. The maintenance arrangement 3 is the most costly option for highways agencies due to roadworks at nighttime only. It can be seen that a maintenance schedule for the daytime with a break during peak hours, i.e. maintenance arrangement 2, can be used to balance agency cost and road user cost.

5. Optimization of maintenance schedule on example network

5.1 *Optimization of maintenance arrangements on dual carriageway (MG2-R4)*

This section illustrates how to find a daily maintenance schedule, so that the road user cost is minimized. The example link *MG2-R4* is used for illustration and maintenance arrangement 2 (Section 4.1.2) is further analysed, since it is the best trade-off between road user cost and agency cost. The total of 9 h of maintenance, split between two time slots with a break between them, is searched for. The constraints for the variables in Section 2 are formulated as follows:

$$7 \leqslant T_S \leqslant 12 \tag{12a}$$

$$2 \leqslant D_{m,1} \leqslant 6 \tag{12b}$$

$$2 \leqslant D_{m,2} \leqslant 6 \tag{12c}$$

$$1 \leqslant B_m \leqslant 2 \tag{12d}$$

$$T_s + D_{m,1} + B_m + D_{m,2} \leqslant 23 \tag{12e}$$

In summary, the first constraint in Equation (12a) means that the start time of maintenance work is sometime between 7:00 and 12:00. The second and third constraints in Equations (12b) and (12c), respectively, limit the duration of each maintenance time slot with the minimum of 2 h and maximum

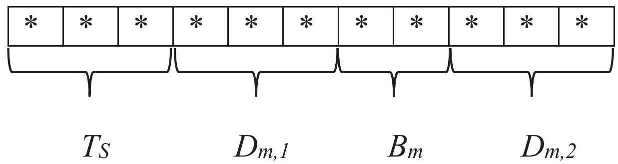

FIG. 3. A typical genotype of chromosome for road link MG2-R4.

of 6 h. The fourth constraint in Equation (12d) means that the break can be 1 or 2 h. The fifth constraint in Equation (12e) means that the maintenance work must be completed by 23:00, so that no nighttime roadworks are carried out.

Based on the variables listed above, the number of working days, for road link *MG2-R4* is calculated by Equation (10). Note, the desired maintenance duration, *MD*, for road link *MG2-R4* is 101 h, as shown in Equation (2). Once the schedule is obtained, the total cost under each maintenance arrangement is achieved using Equation (11).

In this application, the decision variables are recognized as four strings of genes that formed a chromosome in the optimization of maintenance arrangements using the algorithm of binary coded single-objective GAs. The whole chromosome is represented as in Fig. 3 where '*' represents a binary variable, i.e. 0 or 1.

In the optimization control, the size of parent pool is selected as 100, and the crossover rate and mutation rate are adopted as 0.8 and 0.01, respectively, the maximum generation is 500. As the aim of this study is to find the maintenance schedule that resulted in the least travel delay, the objective function is defined as the total road user cost spent during the whole maintenance period, as shown in Equation (8). After the simulation, the best chromosome for all the generations is formed as 111-101-11-011, and then it is decoded to integer numbers where the left end of the string is recognized as the first allele. For example, the fourth string 011 for md_2 is decoded as

$$D_{m,2} = \frac{0 \times 2^0 + 1 \times 2^1 + 1 \times 2^2}{2^3 - 1} \times (6 - 2) + 2 = 5$$

According to the results obtained from GA, the optimal maintenance arrangements are listed as follows:

- T_s 12:00, i.e. start maintenance at midday.
- $D_{m,1}$ 12:00–16:00, i.e. carry out maintenance for 4 h.
- B_m 16:00–18:00, i.e. have a break for 2 h.
- $D_{m,2}$ 18:00–23:00, i.e. carry out maintenance for 5 h
- D_{work} 15 days, i.e. the schedule would follow for 15 days, as shown in Equation (10).

Consequently, the additional road user cost spent on the network during maintenance under the optimal schedule is obtained as £1,009,098 and the corresponding maintenance cost is £114,000. Comparing with the results for the network under maintenance arrangement 2, described in Table 6, shows that the additional cost to road users is greatly reduced by choosing an optimal schedule. Owing to a similar schedule of hours for maintenance between the whole set up and the optimal schedule, similar maintenance cost incurred.

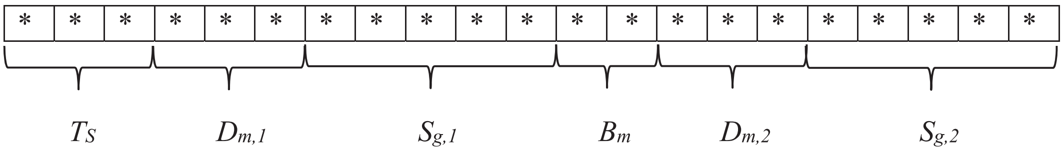

FIG. 4. A typical genotype of chromosome for road link SR2-R4.

5.2 *Optimization of maintenance arrangements on single carriageway (SR2-R4)*

The optimization routine is also applied to find the optimal maintenance schedule on a single carriageway. Take the road link *SR2-R4*, maintenance action 1 is applied, which requires 168 working hours. In addition to the decision variables studied in Section 5.1, the green splits for both directions on a road link during maintenance can also be optimized. Consequently, six decision variables are considered, including start time of maintenance, *st*, maintenance duration 1, md_1, green split for eastbound traffic during maintenance duration 1, $S_{g,1}$, maintenance break, *mb*, maintenance duration 2, md_2, and green split for eastbound traffic during maintenance duration 2, $S_{g,1}$ and $S_{g,2}$ are expressed in % of the cycle. Note that the green split for westbound traffic on road link *SR2-R4* during maintenance duration i is evaluated as $(100 - S_{g,i})$%-*amber phase*. The constraints for the decision variables are described as

$$7 \leqslant T_s \leqslant 12 \tag{13a}$$

$$2 \leqslant D_{m,1} \leqslant 6 \tag{13b}$$

$$2 \leqslant D_{m,2} \leqslant 6 \tag{13c}$$

$$30 \leqslant S_{g,1} \leqslant 60 \tag{13d}$$

$$30 \leqslant S_{g,2} \leqslant 60 \tag{13e}$$

$$1 \leqslant B_m \leqslant 2 \tag{13f}$$

$$T_s + D_{m,1} + B_m + D_{m,2} \leqslant 23 \tag{13g}$$

The fourth and fifth constraints in (13d) and (13e) restrict the green split for eastbound traffic on road link *SR2-R4*, which varies from 30 to 60% of the total cycle. The rest of the constraints are the ones provided in Section 5.1. The chromosome for road link *SR2-R4* is formulated as given in Fig. 4.

In the optimization control, the size of parent pool is selected as 100, and the crossover rate and mutation rate are also adopted as 0.8 and 0.01, respectively, the maximum generation is 500. According to the simulation results, the optimal chromosome is obtained as 011-111-11110-11-101-11110, which represents the following maintenance schedule on the single carriageway:

- T_s 11:00.
- $D_{m,1}$ 11:00–17:00.
- $S_{g,1}$ 44%.
- B_m 17:00–19:00.
- $D_{m,2}$ 19:00–23:00.
- $S_{g,2}$ 44%.
- D_{work} 21 days.

Based on this optimal maintenance schedule, 21 working days are required and the resulting additional road user cost is evaluated as £66,177.3, and the corresponding maintenance cost is £147,000. Compare it with some results of maintenance at night on non-stop day and night (maintenance arrangement 3 in Table 6) for this carriageway, we found that the additional road user cost is small and the corresponding maintenance cost is also reduced by implementing daytime operation.

6. Conclusions and future work

This paper investigates the agency cost and road user cost incurred on the network under various maintenance arrangements, where different parameters, such as start time of maintenance, the allocation of maintenance time slot, maintenance break and traffic control measures are taken into account. The maintenance arrangements for road sections under maintenance can be optimized using GA to facilitate the traffic through the worksite based on NTFM so as to cause fewer disturbances to road users, where the trade-off between the maintenance cost and road user cost is taken into account. The results indicated that nighttime operation led to the least disruption to road users, and the travel delays to road users resulted from daytime operation can be greatly minimized by optimizing maintenance arrangements. However, when the additional road user cost due to daytime maintenance operation is acceptable, highways agencies can carry out daytime operation in order to guarantee the safety of road workers and minimize the possibility of the occurrence of more severe accidents. This paper therefore presents a methodology of how to plan maintenance actions when this trade-off is considered.

The model can be used to evaluate different maintenance arrangements on the network. A list of assumptions has been used to describe such scenarios, to name a few, the duration and maintenance cost of daytime and nighttime works, the continuity of works throughout the day and traffic signal controls in the area of works. According to these assumptions the values of relevant variables are assigned within the tool and the outcomes for the chosen scenarios are demonstrated in the paper. If the tool that supports the developed model was to be used by a transport network maintenance manager, the values of those variables can be varied to fit their requirements and the current practice in the sector. This would ensure that relevant scenarios are implemented and compared. In this approach only the maintenance activities on road links are taken into account by the NTFM, thus the impact of maintenance activities at the junctions could be investigated in the future. Additional rules, such as speed reductions due to the enforcement of worker safety at worksites and the evaluation of vehicle operating cost, and pavement deteriorations models could be taken account of in the future.

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