Algorithm for the Planning of Optimum Highway Work Zones

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Abstract: Work zones often cause traffic congestion on high volume roads. As traffic volumes increase so does work zone-related traffic congestion and so does the public demand for road agencies to decrease both their number and duration. Negative impacts on road users can be minimized by bundling interventions on several interconnected road sections instead of treating each road section separately. Negative impacts on road users can be quantified in user costs. The optimum work zone is the one that results in the minimum overall agency and user costs. The minimization of these costs is often the goal of corridor planning. In order to achieve this goal the interventions on each asset type (pavement, bridges, tunnels, hardware, etc.) must be bundled into optimum packages. In this paper a method is presented that enables road agencies to determine optimum work zones and intervention packages. The method allows the consideration of both budget constraints and distance constraints, including maximum permissible work zone length or minimum distance between work zones. The mathematical formulation of this optimization problem is a binary program that can be solved by existing techniques (i.e., the branch-and-bound method). The feasibility of the approach is illustrated with a simple example.

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Introduction

In the management of road infrastructure agencies are increasingly following the popular corridor approach to plan work zones. In this approach, agencies combine several interventions on a highway into a single intervention package in order to minimize the negative impact on road users (i.e., to find the optimum balance between agency expenditures and user costs). It is a response to public demand for road builders to "get in, get out, and stay out."

Corridors can be either static or dynamic. Static corridors are those that are defined by the administrative partitioning of the road network and do not change over several funding periods. The intervention packages and corresponding work zones, confined to these static corridors, are selected in order to minimize overall costs. This task is similar to determining optimum interventions for a group of assets (e.g., a set of bridges and a set of pavement sections). This task can be accomplished using established methods (e.g., incremental cost/benefit ratio). Dynamic corridors are those that are defined by chosen interventions and are therefore identical to work zones. Hence they change over funding periods. The intervention packages and corresponding work zones (dynamic corridor) for the forthcoming funding period are those that result from the optimization procedure that minimizes overall costs (ASTRA 2000).

This problem of finding optimum dynamic corridors is related to the scheduling of work zones, which is a timely research topic. Traditionally, the major focus of research on highway intervention scheduling was resource allocation [e.g., budget, manpower, material equipment and time (Kallas 1983)]. Recently, however, other aspects such as those on traffic have been gaining in prominence. For instance Fwa et al. (1998) developed a scheduling methodology to minimize traffic delays using a genetic algorithm. An alternative approach, with a somewhat refined traffic delay evaluation, using a tabu search, was developed by Chang et al. (2001). Wang et al. (2002) developed a hybrid scheduling methodology combining a genetic algorithm and microscopic traffic simulations. The goal of these studies was to determine optimum schedules for specific interventions.

The goal of the study discussed in this paper is to combine several interventions on highways components, such as bridges and pavement sections, into a single intervention package. This paper describes a model that can be used to determine optimum intervention packages and their corresponding work zones for the forthcoming funding period on road networks. The length of corridor and the traffic configuration are dependent on the intervention package. Chen et al. (2005) investigated a similar problem—the selection of the optimum work zone considering both user and agency costs with regard to traffic configuration, length, and speed using simulated annealing.

Framework and Required Data

Interventions, and consequently intervention packages, are characterized in monetary terms. This means that the impact on road users such as loss of time and accidents are expressed monetarily. The optimum intervention package is the one that minimizes the overall long-term agency and user costs. Since the methodology

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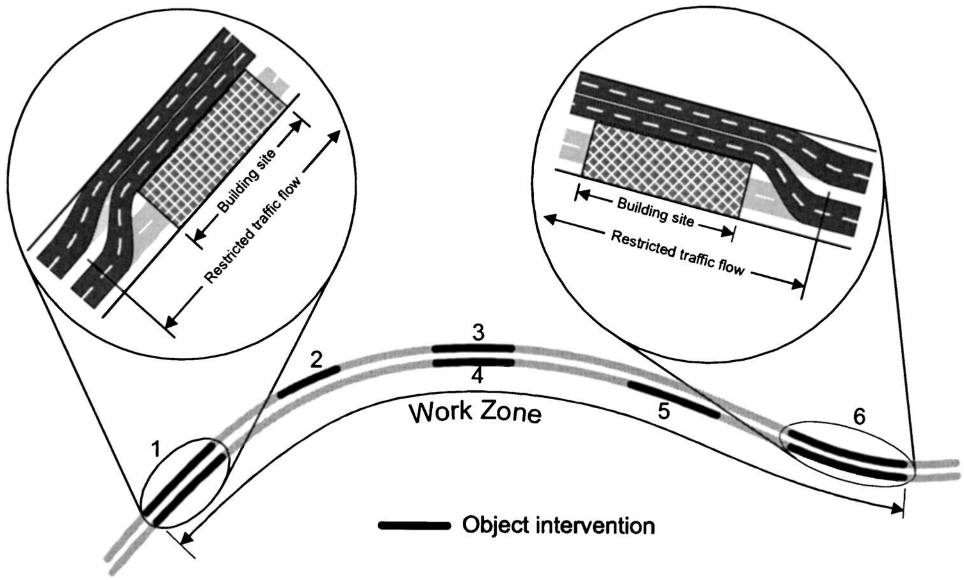

Fig. 1. Work zone illustration

used to estimate user costs is a subject of lively research activity (Yi et al. 1999), it is necessary to state that the methodology used in this paper is based on ASTRA (1998) and Scazziga (1998). Strictly speaking one estimates the change in user costs (i.e., incremental user costs) compared with some reference situation such as one before intervention or sequence of interventions. For the sake of simplicity the attribute "incremental" is omitted in this paper and term "user costs" is used to express the change of user costs.

Interventions are performed on objects, such as sections of pavement, bridges, tunnels, and hardware (guardrails, signs, lighting, barriers, etc.). It is necessary in the planning of these interventions to estimate long-term agency and user costs for each intervention. The long-term agency costs are usually divided into those incurred due to planning and execution of an intervention on an object in the forthcoming funding period, referred to herein as agency costs of intervention, and subsequent agency costs (i.e., those incurred after the intervention is completed, such as subsequent interventions, routine maintenance). The user costs are also divided into those incurred during the intervention (i.e., the user costs of intervention), and subsequent user costs (i.e., those incurred after the intervention). If their sum is negative, which may happen if the intervention is planned and performed, for example, to substantially reduce travel time, these user costs can be referred to as long term user benefits.

Modern pavement and bridge management systems use these cost data to suggest optimum interventions on objects in their respective inventories for the forthcoming funding period. For each object they are able to estimate agency costs, long-term agency costs, user costs, and long-term user costs for several intervention options. The subsequent agency and user costs (i.e., agency and user costs after the intervention option is performed), are estimated by management systems when the optimum intervention strategy is followed, taking into consideration deterioration, discount rate, etc. The optimum intervention for each object is the one that minimizes the sum of long-term agency costs and long-term user costs. This cost data provides the basis for a model described in this paper.

The long-term agency costs of an intervention package consist of two components:

1. Long-term agency costs associated with the objects on which the interventions in the package are performed; and
2. Traffic control costs associated directly with the work zone for which the intervention package is planned.

Long-term agency costs can be approximated by summing the costs associated with each individual object as readily available from management systems. This approximation, strictly taken, is an overestimation, as it neglects the effect of economies of scale (i.e., the reduction of setup costs when interventions are performed on multiple objects). This effect, however, can be neglected due to the low accuracy of estimations of these setup costs.

The fact that subsequent intervention packages and hence the work zones are unknown makes it difficult to estimate the traffic control costs associated with subsequent intervention packages. They are neglected within the framework of this study since they are unlikely to alter the outcome of optimization (i.e., the optimum intervention package). This assumption has been confirmed in practical case studies but should be investigated more thoroughly. The long-term traffic control costs are therefore assumed to be identical to the traffic control costs of an intervention package.

The long-term agency costs of an intervention package E_P (Fig. 1) can be formulated as

$$E_P = \sum_{i=1}^{6} C_i + V_P \qquad (1)$$

where C_i=long-term costs related directly to intervention i; and V_P=traffic control costs of the intervention package P.

The agency costs of an intervention package are approximated in a similar manner as its long-term agency costs, summing the agency costs associated with the objects on which the interventions in the package are performed and the traffic control costs. The agency costs of an intervention package E_P^I can be expressed as

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$$E_P^I = \sum_{i=1}^{6} C_i^I + V_P \tag{2}$$

where C_i^I=agency costs related directly to intervention i, which is to be performed in the forthcoming funding period.

The traffic control costs are

$$V_P = \widetilde{V}_P^I + v_P^I \cdot d_P \tag{3}$$

where $\widetilde{V}_P^I$=traffic control setup costs; v_P^I=traffic control costs per unit length of the work zone; and d_P=length of the work zone.

Unfortunately, it is not possible to simply sum the user costs for each intervention that comprises an intervention package to determine the user costs of an intervention package. The estimation of user costs is based on "weakest-link" approach. The user costs are, mostly, governed by the lowest traffic capacity between two junctions. In other words if an intervention on one object requires two-lane, two-way operations (TLTWO), this traffic configuration can be extended along the whole highway section between two junctions with a negligible effect on user costs. In actuality they will increase marginally due to additional accident costs and operational costs, but this increase in negligible for the purpose of planning interventions.

For the work zone shown in Fig. 1 four lanes are squeezed on one roadway and the other is free for construction work. This traffic configuration is often referred as 4+0. The lanes are, however, narrower than the lane widths beyond the work zone and there are no shoulders. The capacity of the highway along the work zone is therefore reduced leading to increased travel times and presumably higher accident rates. The increase in travel time depends on traffic volume. If the traffic volume is sufficiently low to permit uncongested flow, then the increase in travel time will only be due to reduced travel speed along the work zone. If there is congested traffic flow the increase in travel time is the sum of additional time required upstream of the work zone (e.g., due to "stop-and-go" traffic) and the increased travel time due to reduced travel speed along the work zone. The user costs due to increased travel time consist therefore of a fixed portion due to the change in traffic configuration and a length-dependent portion due to the traffic configuration along the work zone. The accidents costs can be expressed in similar way—that is, as a fixed portion due to the change in traffic configuration and a length-dependent portion due to the traffic configuration along the work zone. Since the effects of work zones on traffic flow are not the same in both directions, user costs are direction specific.

The user costs of intervention package U_P^I for the work zone in Fig. 1 can be estimated as follows:

$$U_P^I = \widetilde{U}_{P+}^I + u_{P+}^I \cdot d_{P+} + \widetilde{U}_{P-}^I + u_{P-}^I \cdot d_{P-} \tag{4}$$

where $\widetilde{U}_P^I$=user costs due to the change in traffic configuration; u_P^I=user costs per unit length of the work zone; and d_P=length of the work zone. The + sign indicates that the traffic flows in the direction of increasing mileage, and the − sign indicates that the traffic flows in the direction of decreasing mileage. The user costs due to the change in traffic configuration $\widetilde{U}_P^I$ must be estimated beforehand using, for example, a traffic simulation program. They depend on upstream traffic assumptions and have to be corrected iteratively if there are multiple work zones on the network as discussed by Wang et al. (2002).

An intervention package that is planned to reduce or alleviate existing traffic disruptions will decrease travel times and accident rates and therefore result in a long-term reduction of user costs (i.e., user benefits). This long-term user cost (or benefit) of intervention package can be given by

$$U_P = U_P^I + B_P \tag{5}$$

where B_P=user benefits. Preservation packages (intervention packages aimed at restoring the initial condition of the objects) will generally not have any user benefit, whereas improvement packages (interventions packages aimed at improving the performance of the infrastructure) will result in user benefit. In addition to this user benefit, user costs during subsequent interventions on the objects in the work zone can be expected. Since subsequent intervention packages are generally unknown, these costs are also unknown. Subsequent interventions on objects in the work zone are, however, generally known, and if executed singly, related traffic configuration can be assumed. Based on this assumption one can estimate the user costs during subsequent interventions on single objects. The maximum of these user costs can serve as a rough estimate for subsequent intervention packages for this work zone. These rough estimates have been used to test the importance of long-term user costs in practical case studies. Since they didn't have a significant impact on optimization results (i.e., on the optimum intervention package), they are neglected in further problem formulation.

In order to evaluate intervention packages as discussed above the following data on object interventions are required:

- Long-term agency costs of intervention (as previously defined);
- Agency cost of intervention (as previously defined);
- Location and extent of the object on which the interventions are planned, using linear coordinates (e.g., kilometers or mileage);
- Traffic configuration required for each intervention, taking into consideration that there are limited numbers of lane patterns allowed on high volume highway sections (traffic configurations include the options of lane closure or reduction of lane width); and
- Execution time frame within which the proposed intervention is valid. Since the object interventions are planned to alleviate object deficiencies, such as physical damages or functional shortcomings, and these deficiencies change in time, the planned intervention will only be suitable for a limited period of time.

These data can be provided by management systems for each asset type, such as modern bridge (Hajdin and Grob 1995) and pavement management systems.

Problem Formulation

General

To determine the optimal work zone on a highway network, it is necessary to evaluate all possible combinations of interventions that might be included in the intervention package and the long-term costs and benefits of each combination. One way to find the optimum intervention package, and therefore the optimal dynamic highway work zone, is an exhaustive search of all combinations of interventions. Exhaustive enumeration, however, is not always possible due to the combinatorial complexity. The number of possible work zones grows exponentially with the number of objects in need of intervention; that is

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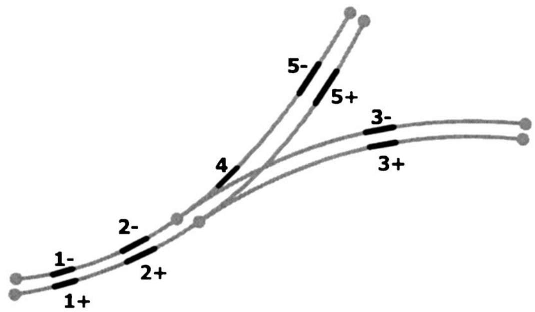

Fig. 2. Road section with possible interventions

$$n_p = 2^n \tag{6}$$

where n_P=number of possible work zones; and n=number of objects in need of intervention along an arbitrary path in network.

Another way to find the optimum intervention package is to formulate the optimization problem as a network problem. This alone, however, does not reduce the computational complexity, but it allows the introduction of length constraints both with regard to the work zone and to the distance between work zones. In practice these constraints significantly reduce the complexity of the problem.

Formulated as a network problem the highway network must be represented by a network model. This model must be directional and each intervention conceptually divided into two distinct interventions since work zones do not affect traffic flow in the same way in both directions as previously mentioned. Intervention costs can, however, be arbitrarily divided between these "directed" interventions, since either none or both are going to be executed. An example of this division is illustrated on the directional model of an example road network shown in Fig. 2. The road sections where interventions are planned herein are indicated with black lines.

Network Model

When formulating the optimum work zone problem, the highway network is modeled as a directed graph where its nodes are either the start or end points of interventions, road intersections, or network limits. In addition, two fictitious nodes are added, so that the network has only two end points. The nodes of the physical network are shown in Fig. 3. The network model of the physical network is shown in Fig. 4. In this network model arcs either represent sections of highway where objects that are subject to possible intervention are located, or sections of highway where no interventions are planned. The latter can be subject to traffic restrictions due to the bundling of work zones. Long-term costs and benefits are assigned to each arc. The optimum intervention packages and corresponding work zones are then given by the directed paths (i.e., sequence of distinct arcs between the start and end node) that minimizes long-term costs. This formulation is similar to a minimum-cost flow problem.

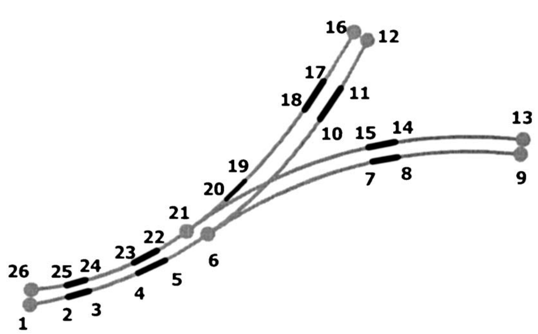

Fig. 3. Physical nodes

If multiple interventions are possible on an object, each intervention with the corresponding traffic configuration has to be represented by an arc. In this expanded network model the nodes are generated by taking into consideration the location of the physical nodes and the possible traffic configurations of adjoining arcs. The nodes are either:

- Start or end points of the traffic configurations related to each possible intervention;
- Road intersections; or
- Network limits.

The expanded network model for the example network for unidirectional traffic flow is shown in Fig. 5. In addition to the "do nothing" intervention and the associated unrestricted traffic configuration, two interventions with corresponding traffic configurations (e.g., 3+1 and 4+0) are introduced. It is assumed that each intervention has a unique traffic configuration for a given road section. The traffic configuration 1 (3+1) is represented in Fig. 5 by the path [1,0]-[2,1]-[3,1]-[4,1], etc.

In terms of notation it is considered that the previously mentioned expanded network model $G=(N,A)$ consists of nodes N and arcs A. The arcs are defined by ordered pairs of nodes $([i,k],[j,l]) \in A$ where the physical nodes are indicated with i and j, and the traffic configurations are indicated with k and l. The subset N_v includes the nodes that represent forking [e.g., nodes [6,1], [6,0], and [6,2] in Fig. 5] and the subset N_z merging nodes in the highway network (not represented in Fig. 5).

Arc Values

The arc values in the network model represent the long-term costs and it is the sum of these values that is minimized in the objective function. For the arc $([i,k],[j,l])$, they are given by

$$C_{[i,k][j,l]} + V_{[i,k][j,l]} + U_{[i,k][j,l]} \tag{7}$$

where $C_{[i,k][j,k]}$=long-term agency costs without traffic control costs; $V_{[i,k][j,l]}$=traffic control costs; and $U_{[i,k][j,l]}$=long-term user costs.

The long-term agency costs in Eq. (7) are costs of "directed" interventions. As mentioned before, the sum of these costs and the costs of the intervention in the opposite direction are equal to the long term agency costs of intervention on the object

$$C_{[i,k][j,l]} + C_{[i',k'][j',l']} = C_O \tag{8}$$

where $C_{[i',k'][j',l']}$=cost of the opposite direction intervention; and C_O=total long term agency costs.

The traffic control costs for each arc that represents a change in traffic configuration can be expressed as in Eq. (3)

$$V_{[i,k][j,l]} = \tilde{V}_{kl}^{I} + v_{kl}^{I} \cdot d_{ij} \tag{9}$$

where $\tilde{V}_{kl}^{I}$=setup costs of a change in traffic configuration from k to l; v_{kl}^{I}=cost per unit length of the change itself from k to l; and d_{ij}=length between nodes i and j.

The traffic control costs for each arc that represents a portion of the network where there is no change in traffic configuration have only a length-dependent portion:

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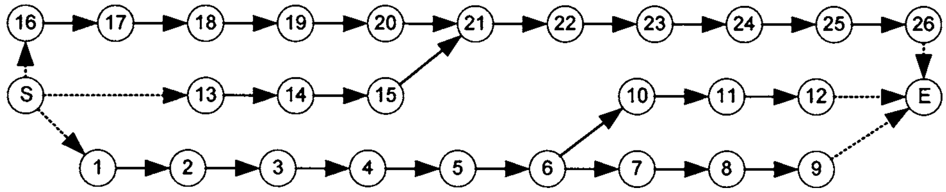

Fig. 4. Network model (directed graph) without intervention options

$$V_{[i,k][j,k]} = v^I_{kk} \cdot d_{ij} \quad (10)$$

where v^I_{kk}=cost per unit length of maintaining the traffic configuration.

It should be noted that in Eqs. (9) and (10) traffic control costs do not depend on the location of the traffic configuration. This simplification will be discussed in course of further research.

The user costs on arcs where a change in traffic configuration occurs have a fixed and a length-dependent portion

$$U^I_{[i,k][j,l]} = \tilde{U}^I_{[i,k][j,l]} + u^I_{[i,k][j,l]} \cdot d_{ij} \quad (11)$$

where $\tilde{U}^I_{[i,k][j,l]}$=user costs incurred upstream of the work zone (e.g., due to "stop-and-go" traffic) and the increased accident rate due to the changing of traffic configurations; and $u^I_{[i,k][j,l]}$=user costs per unit length that are incurred in the work zone. It should be noted that both $\tilde{U}^I_{[i,k][j,l]}$ and $u^I_{[i,k][j,l]}$ depend on incoming traffic volume, which can be influenced by other intervention packages. This means that if minimum costs require multiple intervention packages, the dependency between these intervention packages with regard to traffic volume must be taken into consideration. In practice, however, the required minimum distance between the intervention packages is often large enough so that the intervention packages may be considered independent with respect to traffic flow. Based on practical experience and performed simulation on the Swiss National Highway Network it is considered that the 50-km distance between work zones is sufficient to warrant independency.

The user costs for arcs that represent road sections where there are no changes in traffic configuration consist only of a length-dependent portion

$$U^I_{[i,k][j,k]} = u^I_{kk} \cdot d_{ij} \quad (12)$$

where u^I_{kk}=user costs per unit length along the traffic configuration k.

Long-term user benefits from improvement interventions can in some cases be assigned to interventions and hence to an arc in network model. The examples are the reduction of bottlenecks that may be associated with obsolete bridges or the alleviation of localized safety problems. These user benefits can be simply subtracted from long-term agency costs. In most cases, however, user benefits cannot be assigned to an improvement intervention on a single object but rather to an improvement package, and therefore must be treated separately. Some examples of improvement packages are the widening of the highway between two intersections or the reinforcement of bridges on a certain road section. Since no long-term user benefits can be assigned to these arcs, the long-term user costs are identical to the user costs of interventions

$$U_{[i,k][j,k]} = U^I_{[i,k][j,k]} \quad (13)$$

The long-term user benefits are only obtained once all required interventions between two intersections are performed. If, for instance, a single bridge between two intersections is not widened, the intended benefit will not materialize. It should be noted that if improvement interventions are planned on multiple road sections then there can be a dependency between them with regard to

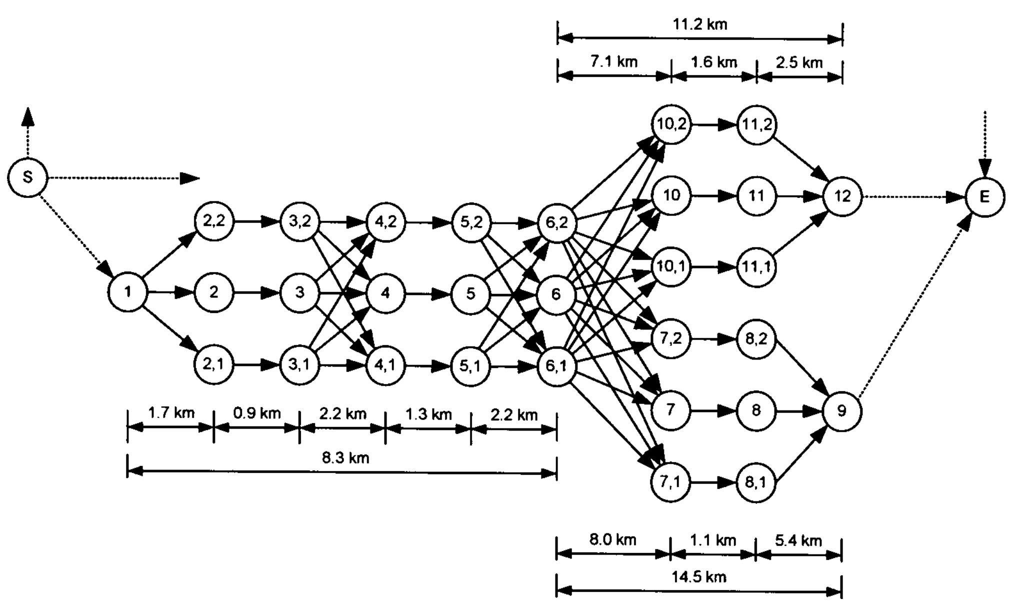

Fig. 5. Network model (directed graph) with intervention options

long-term user benefits. In this study it is assumed that the long-term benefits of the road sections eligible for improvement are independent.

Objective Function

The goal of the objective function of the optimal work zone problem is to minimize long-term costs on the network

$$\text{Min } Z = \sum_{([i,k][j,l])\in A} y_{[i,k][j,l]} \cdot (C_{[i,k][j,l]} + V_{[i,k][j,l]} + U_{[i,k][j,l]}) - \sum_{m=1}^{M} \eta_m \cdot B_m \tag{14}$$

where $y_{[i,k][j,l]}$=binary variable that takes the value of 1 if arc $[i,k][j,l]$ belongs to the path that minimizes Z and 0 if it does not; M=number of road sections on which improvement interventions are planned; B_m=long-term benefit for section m; and η_m=binary variable that takes the value of 1 if all required improvement interventions on road section m are to be performed and 0 otherwise. The binary variable η_m is subject to following constraint

$$\eta_m \leqslant \frac{\sum_{([i,k][j,l])\in A_m} y_{[i,k][j,l]}}{\sum_{([i,k][j,l])\in A_m} 1} \tag{15}$$

where A_m=set of arcs that must be included in the intervention package in order to trigger long-term user benefits. This constraint is only valid if B_m is assumed to be positive. If B_m can be either positive or negative, the binary variable η_m must be split in two, one for positive values and one for negative values of B_m.

Continuity Constraints

The topology of the network is taken into consideration through the continuity constraints

$$1 = \sum_{[j,l]:(a[j,l])\in A} y_{a[j,l]} \tag{16}$$

$$\sum_{[i,k]:([i,k]e)\in A} y_{[i,k]e} = 1 \tag{17}$$

$$\sum_{[j,l]:([j,l][i,k])\in A} y_{[j,l][i,k]} = \sum_{[j,l]:([i,k][j,l])\in A} y_{[i,k][j,l]} \quad \forall\, [i,k] \notin [N_z \cup N_v] \wedge [i,k] \neq a \wedge [i,k] \neq e \tag{18}$$

where a and e= start and end nodes; respectively. Node a is a source node at which point one unit flows into the network. Node e is a sink node at which point one unit flows out of the network. Eq. (18) does not apply for forking and merging nodes. At forking nodes additional units of flow have to enter the network and at merging point these units have to flow out of the network. The number of outgoing branches at forking node i is α_i and the continuity constraint is

$$\alpha_i \cdot \sum_{[j,l]:([j,l][i,k])\in A} y_{[j,l][i,k]} = \sum_{[j,l]:([i,k][j,l])\in A} y_{[i,k][j,l]} \quad \forall\, [i,k] \in N_v \tag{19}$$

The subset of forking nodes is N_v. In order to ensure that only one unit enters each branch at a forking node the following constraint is introduced

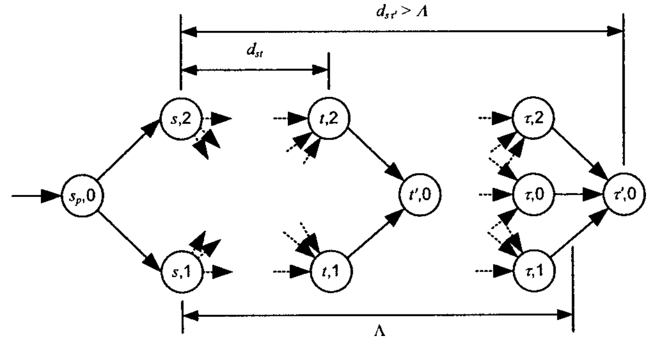

Fig. 6. Maximum work zone length

$$\sum_{[j,l]:([j,l][i,k])\in A_b} y_{[j,l][i,k]} \leqslant 1 \quad \forall\, b \tag{20}$$

The subset of outgoing arcs that belong to this outgoing branch is A_b. The condition in Eq. (20) must hold for each outgoing branch b.

For the merging nodes the following constraints must be met

$$\frac{1}{\alpha_i} \cdot \sum_{[j,l]:([j,l][i,k])\in A} y_{[j,l][i,k]} = \sum_{[j,l]:([i,k][j,l])\in A} y_{[i,k][j,l]} \quad \forall\, [i,k] \in N_z \tag{21}$$

where N_z=set of merging nodes (where multiple branches become one); and α_i=number of branches entering a merging node.

Length and Budgetary Constraints

The solution to the mathematical model defined with Eqs. (14)–(21) is a path (or paths)—a combination of interventions with their associated traffic configurations that can extend over the entire network. If unconstrained, this solution may, however, result in unacceptably long work zones, work zones that are too close together, and/or work zones that are prohibitively expensive. Three additional constraints are therefore required to ensure the desired outcome. In addition these constraints with practical values reduce the complexity of the problem significantly.

The formulation of the maximum work zone length constraint is introduced as follows (Fig. 6). The start of the work zone, node s, is defined by the change in traffic configuration from unrestricted flow to some other traffic configuration

$$\sum_{[s,l]:([s_p,0][s:l])\in A \wedge l\neq 0} y_{[s_p,0][s,l]} = 1 \tag{22}$$

where s_p=node preceding node s taking into consideration the traffic flow direction.

The work zone ends at node τ since the distance from s to the next node τ' in the direction of traffic flow exceeds the maximum work zone length Λ. The road arc $\tau\tau'$ must therefore fulfill the following condition

$$\sum_{[\tau,l]:([\tau,l][\tau',0])\in A} y_{[\tau,l][\tau',0]} = 1 \tag{23}$$

This means that there is a free flow or change to free flow between node τ and node τ'. The distance constraint for maximum work zone length is then formulated as

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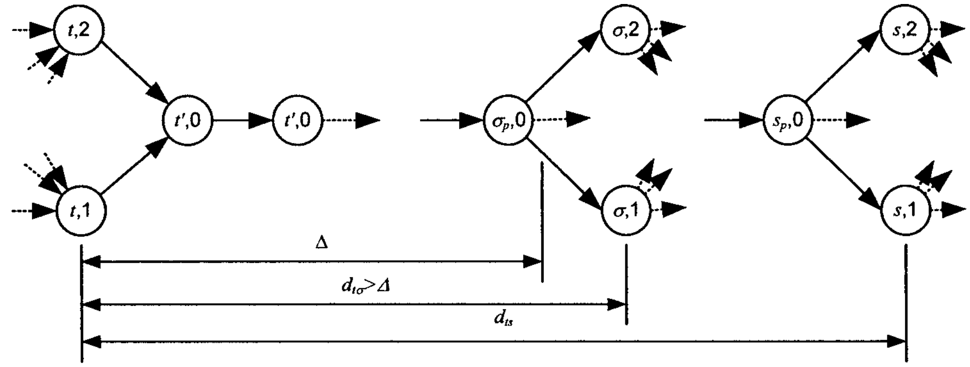

Fig. 7. Minimum distance between work zones

$$\sum_{[s,l]:([s_p,0][s,l])\in A\wedge l\neq 0} y_{[s_p,0][s,l]} - \sum_{[\tau,l]:([\tau,l][\tau',0])\in A} y_{[\tau,l][\tau',0]} \leqslant 0$$
$$\forall s \in N$$
$$d_{s\tau} \leqslant \Lambda \leqslant d_{s\tau'} \tag{24}$$

where $d_{s\tau}$=distance between nodes s and τ. Eq. (24) can be reformulated as follows

$$\sum_{\substack{[s,l]:([s_p,0][s,l])\in A\\ \wedge l\neq 0}} y_{[s_p,0][s,l]} - H((\Lambda - d_{s\tau})\cdot(d_{s\tau'}-\Lambda))$$
$$\times \sum_{[\tau,l]:([\tau,l][\tau',0])\in A} y_{[\tau,l][\tau',0]} \leqslant 0$$
$$\forall\, s \in N \tag{25}$$

where $H(\cdot)$=step function or Heaviside function defined as follows:

$$H(x) = \begin{cases} 0 & x < 0 \\ 1 & x \geqslant 0 \end{cases} \tag{26}$$

The constraint formulation in Eq. (25) is valid if there is only one path between the nodes s and τ. In general there may be several paths in the network between these nodes and some may satisfy the maximum work zone constraint whereas the others may not. In these cases it is necessary to set up constraints for each possible path by introducing intermediate nodes, which define the possible paths. Further discussion on these constraints can be found in Rafi et al. (2005).

The formulation of the minimum distance between work zone constraint is based on similar considerations (Fig. 7). If the work zone ends at node t then

$$\sum_{[t,l]:([t,l][t',0])\in A\wedge l\neq 0} y_{[t,l][t',0]} = 1 \tag{27}$$

where t'=next node taking into consideration the flow of traffic. This means that the start of the work zone is only permitted, at the nearest, at node σ since the distance between node t and node σ is larger and the distance between node t and node σ_p is smaller than the specified minimum distance Δ. The constraint can be formulated as follows:

$$\sum_{[i,0][j,0]\in A'} y_{[i,0][j,0]} = \nu \tag{28}$$

where the subset A' includes all arcs between nodes t and σ_p. This constraint means that there must be free flow between nodes t and σ_p. The constraint in Eq. (28) is only mandatory if Eq. (27) is fulfilled. Hence the following constraints have to be introduced to maintain the minimum distance between work zones

$$\sum_{[i,0][j,0]\in A'} y_{[i,0][j,0]} \geqslant \left(\sum_{[t,l]:([t,l][t',0])\in A\wedge l\neq 0} y_{[t,l][t',0]}\right)\cdot \nu$$
$$\forall t \in N$$
$$d_{t\sigma_p} \leqslant \Delta \leqslant d_{t\sigma} \tag{29}$$

Finally the intervention package is subject to financial constraints. This maximum budget constraint can be formulated as

$$\sum_{([i,k][j,l])\in A} y_{[i,k][j,l]}\cdot(C^l_{[i,k][j,l]} + V^l_{[i,k][j,l]}) \leqslant R \tag{30}$$

where R=maximum resources to be allocated.

Illustrative Example

In order to illustrate the proposed algorithm the example network (Fig. 3) is analyzed. The objects on which interventions are planned are indicated as black lines. It is assumed that for each object three intervention options are possible including the "do nothing" option. The expanded network model is bidirectional, but in this particular example, can be and is simplified to only one direction. The solution determined using a bidirectional model is the same as the one determined using a unidirectional model because all possible paths are covered by the unidirectional model. If however the path 13-14-15-10-11-12 were possible, the unidirectional model would not yield correct results and a bidirectional network would have to be used.

The unidirectional model used in this example is presented in Fig. 5. For each arc the long-term cost of interventions are calculated and presented in Fig. 8. The costs of the interventions are presented in Fig. 9. It is assumed that there are no improvement interventions. The complete formulation of the problem is given in the Appendix.

The formulated mathematical problem in the Appendix is a binary program that can be solved by using a branch-and-bound algorithm or some other established binary programming solution algorithms. In this particular example the branch-and-bound algorithm was used and implemented in an Excel sheet. The physical meaning of the branching in this case can be seen as the decomposition of the problem by the selection of work zone starting points.

The optimum work zone packages were determined for two maximum length constraints (12 and 15 km) and two budgetary constraints (30 monetary units and unlimited). Figs. 10 and 11

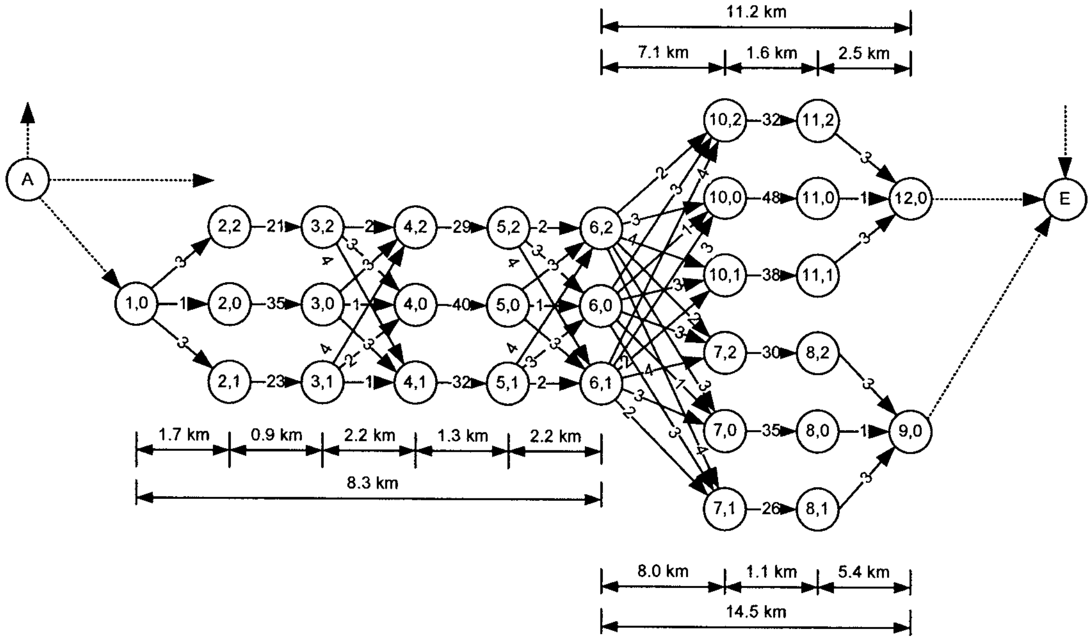

Fig. 8. Long-term cost of interventions

show the optimum work zones when the maximum work zone length is 12 km and the budget is restricted to 30 monetary units, and when the maximum work zone length is 15 km and there is no budget restriction, respectively. For the former, the optimum intervention package contains interventions on objects 2-3 and 4-5 with the traffic configuration 1 (3+1). The long-term costs of this intervention package are 150 monetary units and the agency cost of the intervention package is 24 monetary units. For the latter, the optimum intervention package contains interventions on objects 4-5, 10-11, and 7-8 with the traffic configuration 2 (4+0). The long-term costs of this intervention package are 140 monetary units and the agency cost of the intervention package is 60 monetary units.

Computational Issues

It is well known that in the general case the computational complexity of a binary program grows exponentially with the number of variables. Indeed, if no length constraints are introduced the problem is intractable even for moderately large networks (>300 interventions). With the length constraints used in practice, however, the complexity is dramatically reduced since the network can be branched using binary variables at each possible starting point of work zone. The problem can be additionally simplified if only one intervention package is sought. In this case computational complexity is no longer a hindrance.

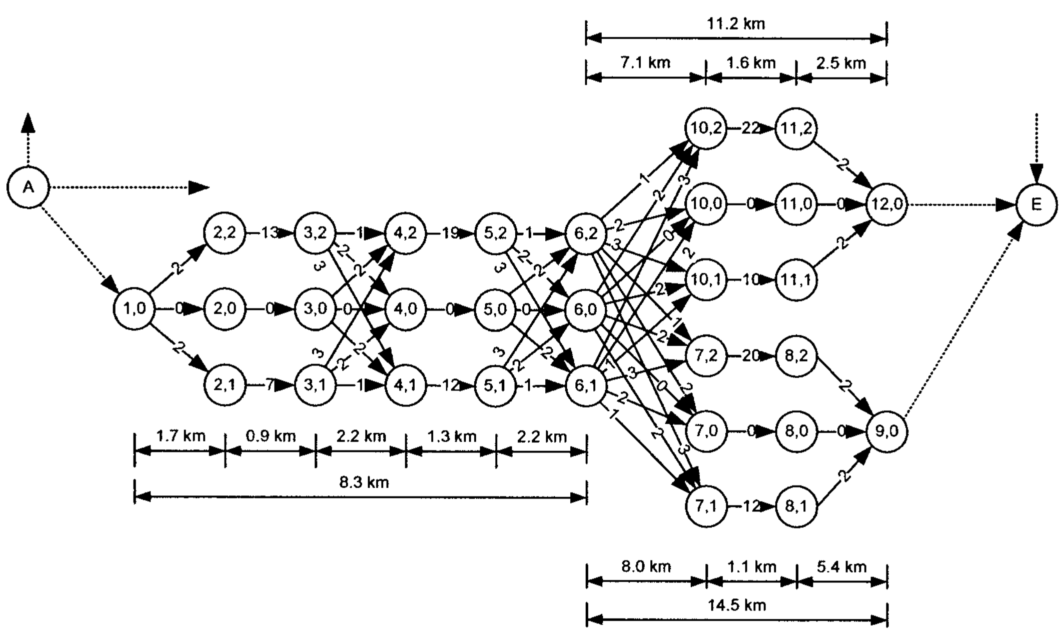

Fig. 9. Cost of interventions

J. Infrastruct. Syst. 2007.13:202-214.

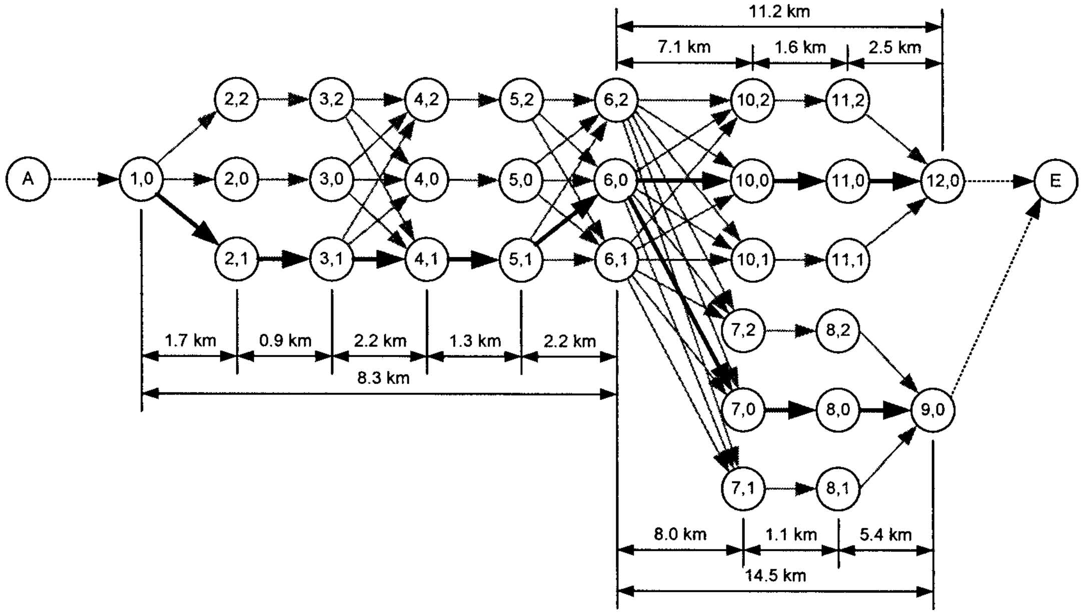

Fig. 10. Optimum corridor: maximum length 12 km/budget 30 MU

In further research the potential of commercial packages will be tested in order to apply the methodology presented in this paper to arterial and community roads, where length constraints are not required.

Conclusions and Outlook

In this paper an analytical model was proposed for a pressing problem in maintenance on high volume highways. The proposed model can be used by decision makers to help plan optimal highway work zones on road networks for a single funding period and a given budget constraint. The work zone and corresponding intervention package is obtained by minimizing long-term agency and user costs. The feasibility of the approach is demonstrated in the illustrative example.

The strength of the proposed model lies in its simplicity, which allows an easy and inexpensive implementation (e.g., Excel). This implementation can be connected to a GIS or to a road topology database in order to retrieve the necessary data for optimization. Furthermore, it is tailored to use results of existing bridge and pavement management systems as inputs for the optimization problem.

The weaknesses of the model, however, also stem from its simplicity. It does not support long-term planning directly, but relies on long-term results from management systems (e.g., bridge

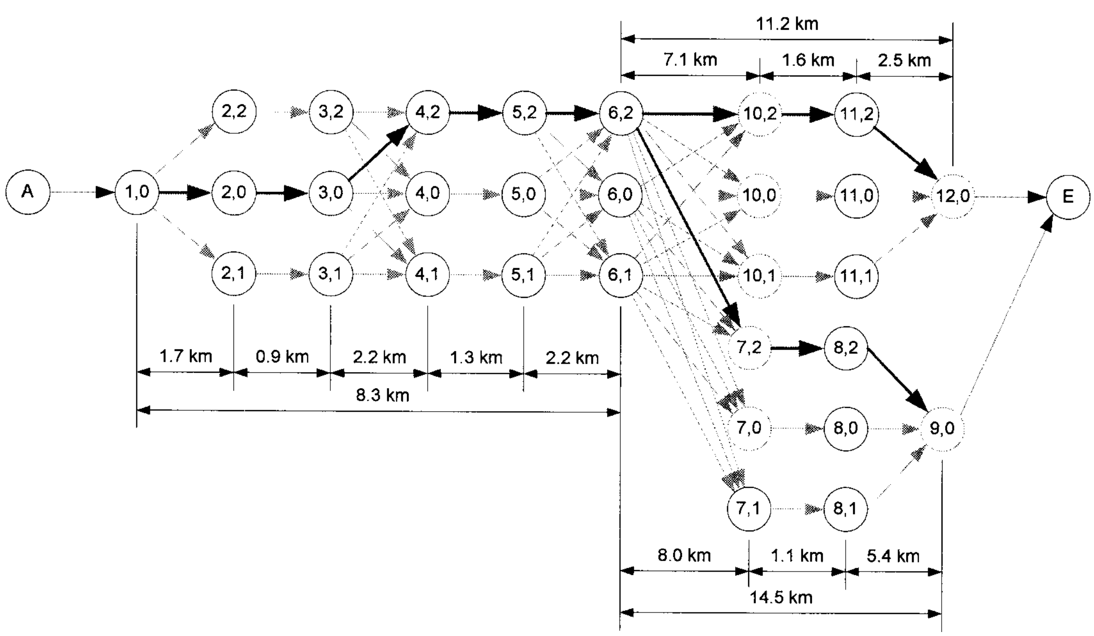

Fig. 11. Optimum corridor: maximum length 15 km/no budget restriction

J. Infrastruct. Syst. 2007.13:202-214.

and pavement management systems). It may yield therefore suboptimal results compared to a more elaborate model, which would optimize intervention packages over several consecutive funding periods. The model furthermore assumes the independency between work zones within the same funding period. This assumption is only justified if the distance between the work zones is sufficiently large. Otherwise one has to perform several iterations in order to obtain useful results.

Further research is currently being focused on:

1. Proving the feasibility of the algorithm on large networks in particular on arterial and community roads;
2. Enhancing performance by exploiting the structure of the binary program; and
3. Taking into consideration interventions that are to be preformed in several consecutive funding periods, as in the proposed algorithm it is assumed that all interventions are to be performed in a single specified funding period.

The second point addresses the possibility of using further organizational and administrative constraints to reduce the complexity of the binary program as well a potential usage of heuristic optimization.

The optimization over several funding periods addressed in the third point is surely a very appealing research topic. The obtained intervention packages over several funding periods would clearly give better guidance to decision makers. It would however vastly increase the computational complexity since network models with intervention options for each funding period have to be combined. Furthermore, the practical benefit of this multiperiod optimization would be limited due to the political nature of the budget process.

Appendix. Mathematical Formulation

The objective function of the problem in Fig. 5 is as follows:

$$\sum_{([i,k][j,l])\in A} y_{[i,k][j,l]}\cdot(C_{[i,k][j,l]}+V_{[i,k][j,l]}+U_{[i,k][j,l]})$$

$$\begin{aligned}&=3y_{[1,0][2,2]}+y_{[1,0][2,0]}+3y_{[1,0][2,1]}+21y_{[2,2][3,2]}+35y_{[2,0][3,0]}+23y_{[2,1][3,1]}+2y_{[3,2][4,2]}+3y_{[3,2][4,0]}+4y_{[3,2][4,1]}+3y_{[3,0][4,2]}+y_{[3,0][4,0]}\\&\quad+3y_{[3,0][4,1]}+4y_{[3,1][4,2]}+3y_{[3,1][4,0]}+2y_{[3,1][4,1]}+29y_{[4,2][5,2]}+40y_{[4,0][5,0]}+32y_{[4,1][5,1]}+2y_{[5,2][6,2]}+3y_{[5,2][6,0]}+4y_{[5,2][6,1]}\\&\quad+3y_{[5,0][6,2]}+y_{[5,0][6,0]}+3y_{[5,0][6,1]}+4y_{[5,1][6,2]}+3y_{[5,1][6,0]}+2y_{[5,1][6,1]}+2y_{[6,2][7,2]}+3y_{[6,2][7,0]}+4y_{[6,2][7,1]}\\&\quad+3y_{[6,0][7,2]}+y_{[6,0][7,0]}+3y_{[6,0][7,1]}+4y_{[6,1][7,2]}+3y_{[6,1][7,0]}+2y_{[6,1][7,1]}+32y_{[7,2][8,2]}+48y_{[7,0][8,0]}+38y_{[7,1][8,1]}+2y_{[6,2][10,2]}\\&\quad+3y_{[6,2][10,0]}+4y_{[6,2][10,1]}+3y_{[6,0][10,2]}+y_{[6,0][10,0]}+3y_{[6,0][10,1]}+4y_{[6,1][10,2]}+3y_{[6,1][10,0]}+2y_{[6,1][10,1]}+30y_{[10,2][11,2]}\\&\quad+35y_{[10,1][11,0]}+26y_{[10,1][11,1]}+3y_{[8,2][9,0]}+y_{[8,0][9,0]}+3y_{[8,1][9,0]}+3y_{[11,2][12,0]}+y_{[11,0][12,0]}+3y_{[11,1][12,0]}=\min!\end{aligned} \tag{31}$$

The continuity constraints for regular nodes (i.e., nonforking and nonmerging nodes), are as follows:

Node 1

$$y_{[1,0][2,2]}+y_{[1,0][2,0]}+y_{[1,0][2,1]}=1 \tag{32}$$

Node 2

$$\begin{aligned}y_{[1,0][2,2]}&=y_{[2,2][3,2]}\\y_{[1,0][2,0]}&=y_{[2,0][3,0]}\\y_{[1,0][2,1]}&=y_{[2,1][3,1]}\end{aligned} \tag{33}$$

Node 3

$$\begin{aligned}y_{[2,2][3,2]}&=y_{[3,2][4,2]}+y_{[3,2][4,0]}+y_{[3,2][4,1]}\\y_{[2,0][3,0]}&=y_{[3,0][4,2]}+y_{[3,0][4,0]}+y_{[3,0][4,1]}\\y_{[2,1][3,1]}&=y_{[3,1][4,2]}+y_{[3,1][4,0]}+y_{[3,1][4,1]}\end{aligned} \tag{34}$$

Node 4

$$\begin{aligned}y_{[3,2][4,2]}+y_{[3,0][4,2]}+y_{[3,1][4,2]}&=y_{[4,2][5,2]}\\y_{[3,2][4,0]}+y_{[3,0][4,0]}+y_{[3,1][4,0]}&=y_{[4,0][5,0]}\\y_{[3,2][4,1]}+y_{[3,0][4,1]}+y_{[3,1][4,1]}&=y_{[4,1][5,1]}\end{aligned} \tag{35}$$

Node 5

$$\begin{aligned}y_{[4,2][5,2]}&=y_{[5,2][6,2]}+y_{[5,2][6,0]}+y_{[5,2][6,1]}\\y_{[4,0][5,0]}&=y_{[5,0][6,2]}+y_{[5,0][6,0]}+y_{[5,0][6,1]}\\y_{[4,1][5,1]}&=y_{[5,1][6,2]}+y_{[5,1][6,0]}+y_{[5,1][6,1]}\end{aligned} \tag{36}$$

Node 10

$$\begin{aligned}y_{[6,2][10,2]}+y_{[6,0][10,2]}+y_{[6,1][10,2]}&=y_{[10,2][11,2]}\\y_{[6,2][10,0]}+y_{[6,0][10,0]}+y_{[6,1][10,0]}&=y_{[10,0][11,0]}\\y_{[6,2][10,1]}+y_{[6,0][10,1]}+y_{[6,1][10,1]}&=y_{[10,1][11,1]}\end{aligned} \tag{37}$$

Node 7

$$\begin{aligned}y_{[6,2][7,2]}+y_{[6,0][7,2]}+y_{[6,1][7,2]}&=y_{[7,2][8,2]}\\y_{[6,2][7,0]}+y_{[6,0][7,0]}+y_{[6,1][7,0]}&=y_{[7,0][8,0]}\\y_{[6,2][7,1]}+y_{[6,0][7,1]}+y_{[6,1][7,1]}&=y_{[7,1][8,1]}\end{aligned} \tag{38}$$

Node 11

$$y_{[10,2][11,2]}=y_{[11,2][12,0]}$$

$$y_{[10,0][11,0]}=y_{[11,0][12,0]}$$

J. Infrastruct. Syst. 2007.13:202-214.

$$y_{[10,1][11,1]} = y_{[11,1][12,0]} \tag{39}$$

Node 8

$$y_{[7,2][8,2]} = y_{[8,2][9,0]}$$

$$y_{[7,0][8,0]} = y_{[8,0][9,0]}$$

$$y_{[7,1][8,1]} = y_{[8,1][9,0]} \tag{40}$$

Node 12

$$y_{[11,2][12,0]} + y_{[11,0][12,0]} + y_{[11,1][12,0]} = 1 \tag{41}$$

Node 9

$$y_{[8,2][9,0]} + y_{[8,0][9,0]} + y_{[8,1][9,0]} = 1 \tag{42}$$

The continuity constraints for forking node 6 are given as follows:

$$2(y_{[5,2][6,2]} + y_{[5,0][6,2]} + y_{[5,1][6,2]}) = y_{[6,2][10,2]} + y_{[6,2][10,0]} + y_{[6,2][10,1]} + y_{[6,2][7,2]} + y_{[6,2][7,0]} + y_{[6,2][7,1]}$$

$$y_{[6,2][10,2]} + y_{[6,2][10,0]} + y_{[6,2][10,1]} \leqslant 1$$

$$y_{[6,2][7,2]} + y_{[6,2][7,0]} + y_{[6,2][7,1]} \leqslant 1$$

$$2(y_{[5,2][6,0]} + y_{[5,0][6,0]} + y_{[5,1][6,0]}) = y_{[6,0][10,2]} + y_{[6,0][10,0]} + y_{[6,0][10,1]} + y_{[6,0][7,2]} + y_{[6,0][7,0]} + y_{[6,0][7,1]}$$

$$y_{[6,0][10,2]} + y_{[6,0][10,0]} + y_{[6,0][10,1]} \leqslant 1$$

$$y_{[6,0][7,2]} + y_{[6,0][7,0]} + y_{[6,0][7,1]} \leqslant 1$$

$$2(y_{[5,2][6,1]} + y_{[5,0][6,1]} + y_{[5,1][6,1]}) = y_{[6,1][10,2]} + y_{[6,1][10,0]} + y_{[6,1][10,1]} + y_{[6,1][7,2]} + y_{[6,1][7,0]} + y_{[6,1][7,1]}$$

$$y_{[6,1][10,2]} + y_{[6,1][10,0]} + y_{[6,1][10,1]} \leqslant 1$$

$$y_{[6,1][7,2]} + y_{[6,1][7,0]} + y_{[6,1][7,1]} \leqslant 1$$

$$y_{[i,j][k,l]} \text{ is binary for } i,k = 1\,..10 \text{ and } j,l = 0\,..2 \tag{43}$$

The maximum budget constraint is formulated as follows:

$$\begin{aligned} &2y_{[1,0][2,2]} + 2y_{[1,0][2,1]} + 13y_{[2,2][3,2]} + 7y_{[2,1][3,1]} + y_{[3,2][4,2]} + 2y_{[3,2][4,0]} + 2y_{[3,2][4,1]} + 2y_{[3,0][4,2]} + 2y_{[3,0][4,1]} + 3y_{[3,1][4,2]} + 2y_{[3,1][4,0]} \\ &\quad + y_{[3,1][4,1]} + 19y_{[4,2][5,2]} + 12y_{[4,1][5,1]} + y_{[5,2][6,2]} + 2y_{[5,2][6,0]} + 3y_{[5,2][6,1]} + 2y_{[5,0][6,2]} + 2y_{[5,0][6,1]} + 3y_{[5,1][6,2]} + 2y_{[5,1][6,0]} + y_{[5,1][6,1]} \\ &\quad + y_{[6,2][7,2]} + 2y_{[6,2][7,0]} + 3y_{[6,2][7,1]} + 2y_{[6,0][7,2]} + 2y_{[6,0][7,1]} + 3y_{[6,1][7,2]} + 2y_{[6,1][7,0]} + y_{[6,1][7,1]} + 20y_{[7,2][8,2]} + 12y_{[7,1][8,1]}y_{[6,2][10,2]} \\ &\quad + 2y_{[6,2][10,0]} + 3y_{[6,2][10,1]} + 2y_{[6,0][10,2]} + 2y_{[6,0][10,1]} + 3y_{[6,1][10,2]} + 2y_{[6,1][10,0]} + y_{[6,1][10,1]} + \; + 22y_{[10,2][11,2]} + 10y_{[10,1][11,1]} + 2y_{[8,2][9,0]} \\ &\quad + 2y_{[8,1][9,0]} + 2y_{[11,2][12,0]} + 2y_{[11,1][12,0]} \leqslant R \end{aligned} \tag{44}$$

For the work zone starting at node 2 and following the branch 6-7-8-9 the maximum length constraint is as follows:

$$\begin{aligned} &y_{[1,0][2,2]} + y_{[1,0][2,1]} - H(\Lambda \cdot (0.9 - \Lambda)) \cdot y_{[2,0][3,0]} - H((\Lambda - 0.9) \cdot (3.1 - \Lambda)) \cdot (y_{[3,2][4,0]} + y_{[3,0][4,0]} + y_{[3,1][4,0]}) - H((\Lambda - 3.1) \cdot (4.4 - \Lambda)) \\ &\quad \cdot y_{[4,0][5,0]} - H((\Lambda - 4.4) \cdot (6.6 - \Lambda)) \cdot (y_{[5,2][6,0]} + y_{[5,0][6,0]} + y_{[5,1][6,0]}) - H((\Lambda - 6.6) \cdot (14.6 - \Lambda)) \cdot (y_{[6,2][7,0]} + y_{[6,0][7,0]} + y_{[6,1][7,0]}) \\ &\quad - H((\Lambda - 14.6) \cdot (15.7 - \Lambda)) \cdot y_{[7,0][8,0]} - H((\Lambda - 15.7) \cdot (21.1 - \Lambda)) \cdot (y_{[8,2][9,0]} + y_{[8,0][9,0]} + y_{[8,1][9,0]}) \leqslant 0 \end{aligned} \tag{45}$$

Similarly, the maximum length constraint for the work zone starting at node 2 and following the branch 6-10-11-12 is given by

$$\begin{aligned} &y_{[1,0][2,2]} + y_{[1,0][2,1]} - H(\Lambda \cdot (0.9 - \Lambda)) \cdot y_{[2,0][3,0]} - H((\Lambda - 0.9) \cdot (3.1 - \Lambda)) \cdot (y_{[3,2][4,0]} + y_{[3,0][4,0]} + y_{[3,1][4,0]}) - H((\Lambda - 3.1) \cdot (4.4 - \Lambda)) \\ &\quad \cdot y_{[4,0][5,0]} - H((\Lambda - 4.4) \cdot (6.6 - \Lambda)) \cdot (y_{[5,2][6,0]} + y_{[5,0][6,0]} + y_{[5,1][6,0]}) - H((\Lambda - 6.6) \cdot (13.7 - \Lambda)) \cdot (y_{[6,2][10,0]} + y_{[6,0][10,0]} + y_{[6,1][10,0]}) \\ &\quad - H((\Lambda - 13.7) \cdot (15.3 - \Lambda)) \cdot y_{[10,0][11,0]} - H((\Lambda - 15.3) \cdot (17.8 - \Lambda)) \cdot (y_{[11,2][12,0]} + y_{[11,0][12,0]} + y_{[11,1][12,0]}) \leqslant 0 \end{aligned} \tag{46}$$

Further constraints for the maximum length of the work zone are formulated as follows:

$$y_{[3,0][4,2]}+y_{[3,0][4,1]}-H(\Lambda\cdot(1.3-\Lambda))\cdot y_{[4,0][5,0]}-H((\Lambda-1.3)\cdot(3.5-\Lambda))\cdot(y_{[5,2][6,0]}+y_{[5,0][6,0]}+y_{[5,1][6,0]})-H((\Lambda-3.5)\cdot(11.5-\Lambda))\cdot(y_{[6,2][7,0]}+y_{[6,0][7,0]}+y_{[6,1][7,0]})-H((\Lambda-11.5)\cdot(12.6-\Lambda))\cdot y_{[7,0][8,0]}-H((\Lambda-12.6)\cdot(18-\Lambda))\cdot(y_{[8,2][9,0]}+y_{[8,0][9,0]}+y_{[8,1][9,0]})\leqslant 0 \quad (47)$$

$$y_{[3,0][4,2]}+y_{[3,0][4,1]}-H(\Lambda\cdot(1.3-\Lambda))\cdot y_{[4,0][5,0]}-H((\Lambda-1.3)\cdot(3.5-\Lambda))\cdot(y_{[5,2][6,0]}+y_{[5,0][6,0]}+y_{[5,1][6,0]})-H((\Lambda-3.5)\cdot(10.6-\Lambda))\cdot(y_{[6,2][10,0]}+y_{[6,0][10,0]}+y_{[6,1][10,0]})-H((\Lambda-10.6)\cdot(12.2-\Lambda))\cdot y_{[10,0][11,0]}-H((\Lambda-12.2)\cdot(14.7-\Lambda))\cdot(y_{[11,2][12,0]}+y_{[11,0][12,0]}+y_{[11,1][12,0]})\leqslant 0 \quad (48)$$

$$y_{[5,0][6,2]}+y_{[5,0][6,1]}-H(\Lambda\cdot(8-\Lambda))\cdot(y_{[6,20][7,0]}+y_{[6,0][7,0]}+y_{[6,1][7,0]})-H((\Lambda-8)\cdot(9.1-\Lambda))\cdot y_{[7,0][8,0]}-H((\Lambda-9.1)\cdot(14.5-\Lambda))\cdot(y_{[8,2][9,0]}+y_{[8,0][9,0]}+y_{[8,1][9,0]})\leqslant 0 \quad (49)$$

$$y_{[5,0][6,2]}+y_{[5,0][6,1]}-H(\Lambda\cdot(7.1-\Lambda))\cdot(y_{[6,2][10,0]}+y_{[6,0][10,0]}+y_{[6,1][10,0]})-H((\Lambda-7.1)\cdot(8.7-\Lambda))\cdot y_{[10,0][11,0]}-H((\Lambda-8.7)\cdot(11.2-\Lambda))\cdot(y_{[11,2][12,0]}+y_{[11,0][12,0]}+y_{[11,1][12,0]})\leqslant 0 \quad (50)$$

$$y_{[6,0][7,1]}+y_{[6,0][7,2]}-H(\Lambda\cdot(1.1-\Lambda))\cdot y_{[7,0][8,0]}-H((\Lambda-1.1)\cdot(6.5-\Lambda))\cdot(y_{[8,2][9,0]}+y_{[8,0][9,0]}+y_{[8,1][9,0]})\leqslant 0 \quad (51)$$

$$y_{[6,0][10,1]}+y_{[6,0][10,2]}-H(\Lambda\cdot(1.6-\Lambda))\cdot y_{[10,0][11,0]}-H((\Lambda-1.6)\cdot(4.1-\Lambda))\cdot(y_{[11,2][12,0]}+y_{[11,0][12,0]}+y_{[11,1][12,0]})\leqslant 0$$

In this example there is no restriction with regard to the minimum distance between work zones.

Notation

The following symbols are used in this paper:

B_m = long-term benefit that can be achieved if all interventions on the road section m are performed;
B_P = long-term benefit of the intervention package;
$C_{[i,k][j,k]}$ = long-term agency costs on arc $([i,j],[k,l])$ (i.e., sum of agency costs of intervention and subsequent costs of intervention);
$C^{\mathrm{I}}_{[i,k][j:l]}$ = agency costs of intervention on arc $([i,j],[k,l])$ in forthcoming funding period;
d_{ij} = distance between nodes i and j;
E_p = long-term agency costs of intervention package p;
E^I_P = agency costs of intervention package p in forthcoming funding period;
M = number of road sections on which improvement actions are planned;
N_v = set of forking nodes (where one arc becomes multiple arcs);
N_z = set of unification nodes (where multiple arcs become one);
n = possible interventions;
n_p = number of possible combinations of interventions;
$U^{\mathrm{I}}_{[i,k][j,l]}$ = user costs of intervention;
$u^{\mathrm{I}}_{[i,k][j,l]}$ = user costs per unit length due to the change of traffic configuration on the arc $([i,j],[k,l])$;
$V_{[i,k][j,l]}$ = traffic control costs on arc $([i,j],[k,l])$;
$\tilde{V}^I_{kl}$ = setup costs of a change in traffic configuration from k to l;
v^I_{kl} = cost per unit length of traffic configuration change from k to l;
y_{ij} = binary variable that takes the value 1 if the edge (i,j) is a part of the solution, and 0 otherwise;
Z = objective function (long-term network costs);
α_i = number of branches leaving a forking node i or entering a merging node i in the network;
Δ = minimum distance between work zones;
η_m = binary variable that takes the value of 1 if all required improvement interventions on road section m are to be performed; and
Λ = maximum work zone length.

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