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A MIXED-INTEGER LINEAR MODEL FOR DETERMINING OPTIMAL WORK ZONES ON A ROAD NETWORK

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Abstract. *One of the tasks of road managers is to determine the interventions to be included in work zones and the traffic configurations to be used during the execution of these interventions. This requires taking into consideration the costs related directly to the objects, such as the manual labour to execute the interventions, and the costs related to the use of the network, e.g. increased noise and increased accidents due to deviated traffic around the work zone that includes the interventions. It also requires balancing the increase in costs during, and the decrease in costs following, the execution of the interventions.*

In this paper a mixed-integer linear model for determining optimal work zones on a road network is presented. In the model, each node represents an intervention on a road segment in the network, and each edge represents a change in the traffic configuration between two road segments. The model is illustrated by determining the optimal work zones (interventions and traffic configuration) on a road network consisting of 160 objects.

1 INTRODUCTION

One of the tasks of road managers is to determine the interventions to be included in work zones and the traffic configurations to be used during the execution of these interventions. This requires taking into consideration the costs related directly to the objects, such as the manual labour to execute the interventions, and the costs related to the use of the network, e.g. increased noise and increased accidents due to deviated traffic around the work zone that includes the interventions. It also requires balancing the increase in costs during, and the decrease in costs following, the execution of the interventions.

Grouping together multiple interventions in a work zone can often lead to the reduction of costs related to the execution of the interventions, e.g. the costs of installing a traffic configuration for two objects is not twice as much as for one object. It also, however, requires the explicit consideration of spatial constraints, i.e. the length of the work zone, and the distance between work zones, in addition to cost constraints, such as the available budget.

Although considerable work has been focused on the determination of the optimal interventions to be executed on road networks over the last few years (e.g. the optimal scheduling of resource allocation [1], [2], the optimal scheduling of specific interventions [3], [4], and the optimal scheduling of interventions at the network level [5], [6]), there has been very little research focused on the optimal grouping of interventions in work zones, herein referred to as optimal work zones (OWZs). Some of the works, however, include that by [7]–[10].

The work done by Hajdin & Lindenmann 2007 is the specific starting point of the work presented in this paper. They proposed a network model to determine OWZs for road infrastructure, in which the nodes were used to represent the ends of a physical object with an intervention, and the edges were used to represent the impacts of travelling from one end of the object with an intervention to the other end of the object with an intervention. They illustrated the model by determining the OWZ on a highway network comprised of 26 objects. The weaknesses of the proposed model are its suitability to be used for larger networks, its inability to be used to determine multiple OWZs simultaneously, and its inability to be used to determine OWZs that span multiple time periods.

The model presented in this paper is an enhancement on the one proposed by [7] as it can be used to determine an optimal set of work zones, simultaneously. This is done by reformulating the structure of the cited model, so that the nodes are used to represent interventions on road segments and edges are used to represent changes in traffic configuration.

2 MODEL

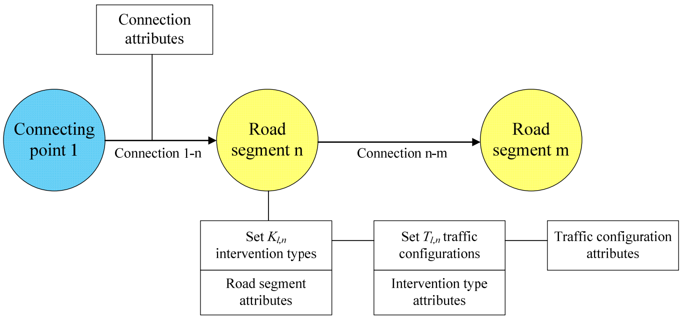
2.1 TERMINOLOGY

A road network is considered to consist of road segments. Each segment is a serial combination of different infrastructure objects (e.g. a road section, a culvert, a bridge, a tunnel). Due to deterioration, the physical condition of objects deteriorate over time and interventions must be executed in order to ensure that the network is able to provide an adequate level of service (LOS). When an intervention is executed on a road segment, it is considered that interventions are executed on all objects within the road segment. There are different types of interventions that can be executed on each object in the network. For example, a road section can be renewed or can be upgraded with partial depth repair. For each type of intervention different types of traffic configurations (TCs) are possible. For example, if crack filling of pavement on a two lane road is to be done there may be either the reduction of the width of both lanes but two lanes remain open, or the closure of one lane and no reduciton in the width of the remaining lane. This concept is summarized in Table 1.

Table 1: Hierarchy of road segments, objects, interventions and traffic configurations

Road segment	Objects	Interventions	Traffic configurations
$l = 1,...,L$	$n_l = 1,...,N_l$	$k_{l,n} = 1,....,K_{l,n}$	$t_{l,n} = 1,...,T_{l,n}$
L: Total number of segments in the network	N_l: Total number of infrastructure objects n segment l	$K_{l,n}$: Total number of interventions on object n in segment l	$T_{l,n}$: Total number of TCs possible for object n in segment l
		$k_{l,n} = 1$ refers to “no intervention”	$t_{l,n} = 1$ refers to the default TC

In the model, each node represents a specific road segment composed of multiple objects. The node also represents an intevention to be executed and a TC to be put in place during the execution of the intervention. The edge represents the change in TC that occurs between the two objects. A further illustration of the hierarchy is given in Fig. 1. This hierarchy makes it easy to use to relate the attributes of one model element to another. Example attributes are given in in Table 2.



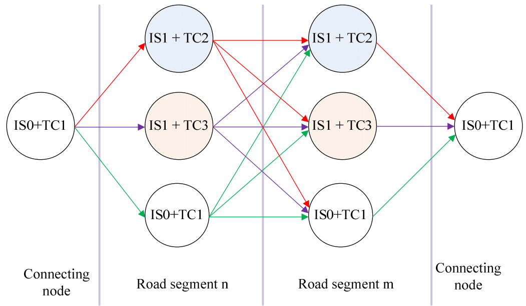


Fig. 1: Illustration of the hierarchy

Fig. 2: Example network model

Table 2: Attribute types

	Type	Examples
nodes	Road segment	Length, number of lanes, DTV, type of infrastructure (e.g. tunnel, bridge, etc.), CS
	Intervention type	Costs (e.g. CHF/m^2), improvement in CS (e.g. from CS 4 to CS 1), production capacity (e.g. m^2/day)
	Traffic configuration	Travel speed, change in accident rate, work space per meter of road (as a result of closing one or more lanes)
links	Connection	Specific attributes that result from a change in TC, e.g. costs for traffic jam at the beginning of a work zone, higher accident rates resulting from the change of the TC

An example of the network model is shown in Fig. 2. It is built for a network with two road segments *n* and *m* and each segment consists of exactly one object. Two types of interventions can be executed on each object, i.e. do nothing and execute an intervention. There is one possible traffic configuration TC1 when no intervention is executed, and there are two possible traffic configurations (TC2 and TC3) when an intervention is executed, i.e. 2 lane restricted traffic flow and 1 lane unrestriced traffic flow. For these two road segments, there are 9 possible work zones that can be formed.

2.2 FORMULATION

The OWZ is found with the following objective function:

$$Maximize \;\; Z = \sum_{l=1}^{L}\sum_{n=1}^{N}\sum_{k=1}^{K}\sum_{t=1}^{T}\delta_{l,n,k,t}\cdot M_{l,n,k,t} - \sum_{e=1}^{E}\gamma_{l,n,k,g-e}\cdot \overrightarrow{N}_{l,n,k,g-e} \tag{1}$$

where

$\delta_{l,n,k,t}$ is a binary variable, which has a value of 1 if an intervention of type *k* is executed on road segment *n* in link *l*, and traffic configuration *t* is used, and 0 otherwise.

$\gamma_{l,n,k,g-e}$ is a binary variable, which has a value of 1 if edge e leaving node [*l*,*n*,*k*,*t*] is selected, and 0 otherwise. E equals the total number of links leaving node [*l*,*n*,*k*,*t*]

$M_{l,n,k,t}$ is the long term benefit of executing an intervention of type *k* with traffic configuration *t* on object *n* in section *l*.

$\overrightarrow{N}_{l,n,k,g-e}$ is the cost, associated with changes between, nodes in the network, for example the cost related to the change in traffic configuration between a road segment with no intervention and a road segment with an intervention

Constraint (2) ensures that only one intervention of type *k* and one traffic configuration of type *t* is selected for road segment *n* of link *l* at one time.

$$\sum_{k=1}^{K}\sum_{t=1}^{T}\delta_{l,n,k,t} = 1 \quad \forall\, l,n \tag{2}$$

Constraint (3) ensures that the sets of road segments upon which interventions are executed are within a WZ, i.e. that if a node is selected than so is an edge leaving the node.

$$\gamma_{l,n,g-e} = \delta_{l,n,k,t} \cdot \delta_e \tag{3}$$

Constraints described by (4) ensure that the costs of each type, e.g. owners costs, stay within given limits. The number of cost constraints in a model depend on the number of stakeholders and cost types that are to be modelled.

$$\sum_{l=1}^{L}\sum_{n=1}^{N}\sum_{k=1}^{K}\sum_{t=1}^{T}\left\{\delta_{l,n,k,t} \cdot \left|P^{s}_{l,n,k,t}\right| + \sum_{e=1}^{E}\varphi_{l,n,k,t-e} \cdot \left|\vec{P}^{s}_{l,n,k,t-e}\right|\right\} \le B^{s} \tag{4}$$

where

$P^{s}_{l,n,k,t}$ is the total cost incurred by stakeholder *s* attributed to the execution of an intervention of type *k* with a traffic configuration of type *t* on object n in link *l*.

$\vec{P}^{s}_{l,n,k,t}$ is the total cost incurred by stakeholder *s* attributed to changes between, nodes in the network.

B^{s} is the maximum allowable costs incurred by stakeholder *s*.

The values of $P^{s}_{l,n,k,t}$ and $\vec{P}^{s}_{l,n,k,t}$ are in fact a part of $M_{l,n,k,t}$ and $\vec{M}_{l,n,k,t-e}$ in Eq. (1), respectively.

Constraint (5) ensures that the WZs do not exceed a specified maximum length. WZs may be limited in maximum length, for example, due to regulations imposed by governing organisations, or due to the capacity of construction companies to run such long construction projects.

$$\sum_{l=a_l^w}^{e_l^w}\sum_{n=a_n^w}^{e_n^w}\lambda_{l,n} \le \Lambda^{MAX} \quad \forall w \tag{5}$$

where

$\lambda_{l,n}$ is the length of the road segment [*l*,*n*];

$a^{w}\ \left(l = a_l^{w}, n = a_n^{w}\right)$ is the first road segment of the WZ $w = (1,\ldots,W)$, and road segment

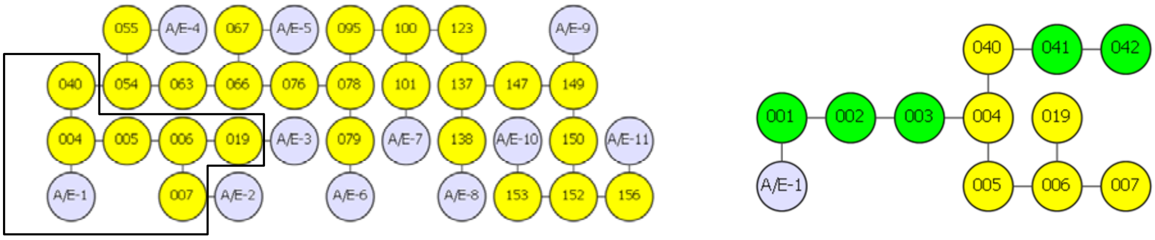
$e^{w}\ \left(l = e_l^{w}, n = e_n^{w}\right)$ is the last road segment in the WZ w.

Λ^{MAX} is maximum allowable length of the WZ.

3 EXAMPLE

3.1 OVERVIEW

In this example the OWZ for a road network consisting of 160 road segments, where each road segment consists of one object (Fig. 3-a, Table 3-Table 4) was determined. The yellow nodes in Fig. 3-a represent the road segments that are either the first or the last road segments in a group of road segments connected in series. The road segments between these are suppressed for illustration purposes. The grey nodes indicate entry and exist points to the network. A partial, but complete, model for the network within the area in Fig. 3-a indicated with the black line is given in Fig. 3-b, where the green nodes are the nodes that have been suppressed in Fig. 3-a.



a-Condensed model of the complete

b-Partial complete model

Fig. 3: physical road network

Table 3. Objects (1-40)

No.	Road type	Object type	Length (km)	DTV	CS	No.	Road type	Object type	Length (km)	DTV	CS
1	HW	tunnel	1.2	38’790	2	41	HW	road	6.6	35’350	3
2	HW	road	5.5	38’790	2	42	HW	bridge	0.3	35’350	2
3	HW	road	6.4	38’790	1	43	HW	road	6.6	37’760	4
4	HW	road	1.2	38’790	2	44	HW	road	4.5	37’760	2
5	CR	road	3.2	13’630	3	45	HW	bridge	1.8	37’760	1
6	CR	tunnel	2.2	13’630	3	46	HW	tunnel	0.7	24’230	4
7	RR	road	1.4	3’820	2	47	HW	bridge	5	24’230	4
8	RR	road	1.7	3’820	1	48	HW	road	7.2	24’230	3
9	MR	road	1.8	3’050	3	49	HW	tunnel	2.5	11’680	4
10	MR	road	1.3	3’050	4	50	HW	bridge	1.3	11’680	3
11	MR	road	2.5	3’050	4	51	CR	road	1.5	10’030	3
12	MR	road	2.6	3’050	5	52	CR	road	1.2	10’030	5
13	MR	road	1.6	3’050	3	53	CR	road	2.1	10’030	4
14	MR	road	2.2	3’050	4	54	CR	road	1.8	10’030	3
15	RR	road	2.5	3’050	4	55	RR	road	1.3	4’030	2
16	RR	road	1	3’050	2	56	RR	road	2.1	4’030	2
17	RR	tunnel	1.2	3’050	1	57	RR	road	2.3	4’030	2
18	RR	road	1.7	3’050	1	58	MR	road	1.8	3’270	3
19	RR	road	1.2	14’390	2	59	MR	road	2.3	3’270	5
20	RR	road	2.2	14’390	2	60	RR	road	1.7	3’270	1
21	RR	road	1.9	12210	2	61	RR	road	1.9	3’270	4
22	RR	bridge	2	12210	4	62	RR	road	1.6	3’270	3
23	RR	tunnel	1.6	12210	3	63	CR	road	2.8	17’010	5
24	RR	road	1.7	12210	4	64	CR	road	2.3	17’010	4
25	RR	road	1.2	6’000	2	65	CR	road	2.6	17’010	3
26	RR	tunnel	0.8	6’000	3	66	CR	road	1.3	17’010	2
27	RR	tunnel	0.6	6’000	1	67	RR	road	1	8’610	5
28	RR	road	1.8	6’000	3	68	RR	road	0.6	8’610	2
29	RR	road	1.1	3’050	4	69	MR	road	1.8	4’800	3
30	RR	road	1.8	3’050	4	70	MR	road	1.4	4’800	4
31	RR	road	1.3	3’050	1	71	RR	tunnel	1.5	4’800	4
32	RR	road	2	3’050	5	72	RR	road	1.2	4’800	4
33	RR	road	1.9	3’050	3	73	RR	tunnel	1	4’800	5
34	RR	road	1.1	3’050	2	74	RR	tunnel	1.3	4’800	5
35	RR	road	2.5	1’740	4	75	RR	road	0.8	4’800	4
36	RR	tunnel	0.6	1’740	4	76	CR	road	3.4	15’920	5
37	RR	road	2.1	1’740	2	77	CR	road	2.7	15’920	2
38	RR	tunnel	5.2	1’740	2	78	CR	road	3	17’770	3
39	RR	tunnel	4.6	1’740	4	79	RR	tunnel	3.2	3’380	1
40	HW	road	6.1	35’350	2	80	RR	bridge	1.2	9’590	4

Note: HW – highway, CR-Cantonal road, RR-regular road, MR-mountain road; CS-condition state

Table 4. Objects (81-160)

No.	Road type	Object type	Length (km)	DTV	CS	No.	Road type	Object type	Length (km)	DTV	CS
81	RR	road	1.9	9’590	5	121	RR	tunnel	3.1	2’500	3
82	RR	road	1.2	9’590	5	122	CR	tunnel	2.6	13410	2
83	RR	bridge	1.7	9’590	4	123	CR	bridge	2.2	7’960	4
84	RR	bridge	1.4	7’410	4	124	RR	road	2.1	7’740	4
85	RR	tunnel	2.3	5’230	2	125	RR	road	2.5	7’630	4
86	RR	road	2.4	5’230	4	126	RR	road	2.1	7’630	4
87	RR	road	1.9	5’230	2	127	RR	bridge	1.8	7’630	4
88	RR	road	2.5	4’360	1	128	MR	bridge	1.8	7’630	4
89	RR	road	2.1	4’360	5	129	RR	road	2.4	7’630	4
90	RR	road	2.5	4’360	2	130	RR	bridge	1.7	4’910	5
91	RR	road	2.1	4’360	3	131	MR	road	2.4	3’600	2
92	RR	bridge	1	3’930	5	132	RR	road	2.7	3’600	5
93	RR	road	2	3’930	3	133	RR	tunnel	2.7	3’600	4
94	RR	road	1.5	3’930	2	134	RR	tunnel	2.8	2’940	5
95	CR	road	1.4	11’670	2	135	RR	road	2.4	2’940	2
96	CR	road	1.9	16’680	2	136	RR	road	2.8	2’940	4
97	CR	road	2.2	21’700	2	137	RR	road	3	2’940	3
98	HW	road	1.4	14’310	1	138	RR	road	1	1’420	1
99	HW	tunnel	1	14’310	2	139	MR	road	1.7	1’420	2
100	HW	road	0.7	14’310	1	140	MR	road	1.4	1’420	5
101	CR	tunnel	1.8	2’500	1	141	MR	road	1.3	1’420	1
102	CR	tunnel	3.2	2’500	5	142	MR	road	1.2	1’420	2
103	RR	road	2.2	2’500	5	143	MR	road	2	1’420	3
104	RR	tunnel	1.3	2’500	2	144	MR	road	1.8	1’420	2
105	RR	tunnel	1.8	2’500	1	145	MR	road	1.8	1’420	2
106	RR	road	2.5	2’500	3	146	MR	road	1.8	1’420	3
107	RR	bridge	0.7	2’500	3	147	RR	road	2.2	2’510	4
108	RR	bridge	2.5	2’500	4	148	RR	tunnel	1.2	2’510	3
109	RR	bridge	2	2’500	2	149	RR	tunnel	1.6	2’510	1
110	RR	tunnel	0.7	2’500	3	150	MR	road	2.6	2’510	4
111	RR	tunnel	1.4	2’500	3	151	MR	road	1.2	2’510	4
112	RR	tunnel	1.7	2’500	4	152	MR	road	2.1	2’510	5
113	RR	road	4.6	2’500	5	153	MR	road	1.8	1’740	4
114	RR	tunnel	1.6	2’500	3	154	MR	road	2.1	1’740	4
115	RR	road	3.4	2’500	5	155	MR	road	2.1	1’740	1
116	RR	tunnel	1.3	2’500	5	156	MR	road	1.9	2’400	2
117	RR	tunnel	1.1	2’500	4	157	MR	road	2.8	2’400	3
118	RR	tunnel	1.6	2’500	4	158	MR	road	1.9	2’400	2
119	RR	tunnel	1.4	2’500	1	159	MR	road	1.9	2’400	2
120	RR	tunnel	2.2	2’500	2	160	MR	road	1.8	2’400	3

3.2 CONDITION STATES

All objects are considered to be in one of five discrete condition states (CS): CS 1 - 5 indicate increasingly poor CSs, where CS 1 is the best condition and CS 2 is the worst condition.

3.3 INTERVENTIONS AND TRAFFIC CONFIGURATIONS

The interventions to be executed on each type of object for each type of road segment when it is in each CS are given in Table 5-Table 8, along with their costs (intervention costs, i.e. the costs of the manual labour, materials and equipment required to execute the interventions; travel time costs, i.e. the costs due to users not being able to travel as normal; accident costs, i.e. the costs due to increases in the accident rate. No interventions are to be executed on objects that are in CS 1 or 2. Traffic configurations considered possible are give in Table 5. Intervention costs are approximated based on historical data and norms [11]. They are broken down into fixed costs and variable costs, where fixed costs are those that are independent of the size of object and variable costs are those dependent on the size of the object.

Table 5. Highway interventions

Object type	CS	IT	TC	Intervention		Loss of travel time	Accidents
				Fixed	Variable		
				CHF	CHF/m^2	CHF/km/day/	CHF/km/day/car
Road section	1, 2,3,4,5	0	0	0	0		
			1	0	0	1.03	0.33
			2	0	0	0.69	0.34
	3	1	1	3’500	8	1.03	0.33
			2	4’200	10	0.69	0.34
	4	2	1	4’100	52	1.03	0.33
			2	4’900	62	0.69	0.34
	5	3	1	9’600	108	1.03	0.33
			2	11’500	130	0.69	0.34
Bridge	1, 2	0	0	0	0	0	0
			1	0	0	0.82	0.34
			2	0	0	2.06	0.36
	3	1	1	20’000	2’100	0.82	0.34
			2	24’000	25’200	2.06	0.36
	4	2	1	30’000	2’800	0.82	0.34
			2	36’000	4’400	2.06	0.36
	5	3	1	40’000	3’500	0.82	0.34
			2	48’000	4’200	2.06	0.36
Tunnel	1, 2	0	0	0	0	0	
			1	0	0	0.82	0.34
			2	0	0	4.11	0.29
	3	1	1	100’000	20’000	0.82	0.34
			2	120’000	24’000	4.11	0.29
	4	2	1	150’000	35’000	0.82	0.34
			2	180’000	42’000	4.11	0.29
	5	3	1	200’000	50’000	0.82	0.34
			2	240’000	60’000	4.11	0.29

Note: CS- condition state; IT-intervention type; TC-traffic configuration

Table 6. Cantonal road interventions

<table>
<tr><th rowspan="3">Object type</th><th rowspan="3">CS</th><th rowspan="3">IT</th><th rowspan="3">TC</th><th colspan="2">Intervention</th><th rowspan="2">Loss of travel time</th><th rowspan="2">Accidents</th></tr>
<tr><th>Fixed</th><th>Variable</th></tr>
<tr><th>CHF</th><th>CHF/m^2</th><th>CHF/km/day/</th><th>CHF/km/day/car</th></tr>
<tr><td rowspan="9">Road section</td><td rowspan="3">1, 2,3,4,5</td><td rowspan="3">0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>1</td><td>0</td><td>0</td><td>1.03</td><td>0.33</td></tr>
<tr><td>2</td><td>0</td><td>0</td><td>0.44</td><td>0.34</td></tr>
<tr><td rowspan="2">3</td><td rowspan="2">1</td><td>1</td><td>3’500</td><td>8</td><td>1.03</td><td>0.33</td></tr>
<tr><td>2</td><td>4’200</td><td>10</td><td>0.44</td><td>0.34</td></tr>
<tr><td rowspan="2">4</td><td rowspan="2">2</td><td>1</td><td>4’100</td><td>52</td><td>1.03</td><td>0.33</td></tr>
<tr><td>2</td><td>4’900</td><td>62</td><td>0.44</td><td>0.34</td></tr>
<tr><td rowspan="2">5</td><td rowspan="2">3</td><td>1</td><td>9’600</td><td>108</td><td>1.03</td><td>0.33</td></tr>
<tr><td>2</td><td>11’500</td><td>130</td><td>0.44</td><td>0.34</td></tr>
<tr><td rowspan="9">Bridge</td><td rowspan="3">1, 2,3,4,5</td><td rowspan="3">0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>1</td><td>0</td><td>0</td><td>0.82</td><td>0.34</td></tr>
<tr><td>2</td><td>0</td><td>0</td><td>4.11</td><td>1.76</td></tr>
<tr><td rowspan="2">3</td><td rowspan="2">1</td><td>1</td><td>20’000</td><td>2’100</td><td>0.82</td><td>0.34</td></tr>
<tr><td>2</td><td>24’000</td><td>25’200</td><td>4.11</td><td>1.76</td></tr>
<tr><td rowspan="2">4</td><td rowspan="2">2</td><td>1</td><td>30’000</td><td>2’800</td><td>0.82</td><td>0.34</td></tr>
<tr><td>2</td><td>36’000</td><td>4’400</td><td>4.11</td><td>1.76</td></tr>
<tr><td rowspan="2">5</td><td rowspan="2">3</td><td>1</td><td>40’000</td><td>3’500</td><td>0.82</td><td>0.34</td></tr>
<tr><td>2</td><td>48’000</td><td>4’200</td><td>4.11</td><td>1.76</td></tr>
<tr><td rowspan="9">Tunnel</td><td rowspan="3">1, 2,3,4,5</td><td rowspan="3">0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>1</td><td>0</td><td>0</td><td>0.82</td><td>0.34</td></tr>
<tr><td>2</td><td>0</td><td>0</td><td>4.11</td><td>4.05</td></tr>
<tr><td rowspan="2">3</td><td rowspan="2">1</td><td>1</td><td>100’000</td><td>20’000</td><td>0.82</td><td>0.34</td></tr>
<tr><td>2</td><td>120’000</td><td>24’000</td><td>4.11</td><td>4.05</td></tr>
<tr><td rowspan="2">4</td><td rowspan="2">2</td><td>1</td><td>150’000</td><td>35’000</td><td>0.82</td><td>0.34</td></tr>
<tr><td>2</td><td>180’000</td><td>42’000</td><td>4.11</td><td>4.05</td></tr>
<tr><td rowspan="2">5</td><td rowspan="2">3</td><td>1</td><td>200’000</td><td>50’000</td><td>0.82</td><td>0.34</td></tr>
<tr><td>2</td><td>240’000</td><td>60’000</td><td>4.11</td><td>4.05</td></tr>
</table>

Table 7. Rural road interventions

Object type	CS	IT	TC	Intervention Fixed CHF	Intervention Variable CHF/m^2	Loss of travel time CHF/km/day/	Accidents CHF/km/day/car
Road section	1, 2,3,4,5	0	0	0	0	0	0
			1	0	0	3.29	0.31
			2	0	0	4.94	2.77
	3	1	1	3’500	8	3.29	0.31
			2	4’200	10	4.94	2.77
	4	2	1	4’100	52	3.29	0.31
			2	4’900	62	4.94	2.77
	5	3	1	9’600	108	3.29	0.31
			2	11’500	130	4.94	2.77
Bridge	1, 2,3,4,5	0	0	0	0	0	0
			1	0	0	1.23	0.33
			2	0	0	4.94	1.76
	3	1	1	20’000	2’100	1.23	0.33
			2	24’000	25’200	4.94	1.76
	4	2	1	30’000	2’800	1.23	0.33
			2	36’000	4’400	4.94	1.76
	5	3	1	40’000	3’500	1.23	0.33
			2	48’000	4’200	4.94	1.76
Tunnel	1, 2,3,4,5	0	0	0	0	0	0
			1	0	0	1.23	0.33
			2	0	0	4.94	1.76
	3	1	1	100’000	20’000	1.23	0.33
			2	120’000	24’000	4.94	1.76
	4	2	1	150’000	35’000	1.23	0.33
			2	180’000	42’000	4.94	1.76
	5	3	1	200’000	50’000	1.23	0.33
			2	240’000	60’000	4.94	1.76

Table 8. Mountain road interventions

Object type	CS	IT	TC	Intervention Fixed CHF	Intervention Variable CHF/m^2	Loss of travel time CHF/km/day/	Accidents CHF/km/day/car
Road section	1, 2,3,4,5	0	0	0	0	0	0
			1	0	0	1.23	0.33
			2	0	0	4.94	4.05
	3	1	1	3’500	8	1.23	0.33
			2	4’200	10	4.94	4.05
	4	2	1	4’100	52	1.23	0.33
			2	4’900	62	4.94	4.05
	5	3	1	9’600	108	1.23	0.33
			2	11’500	130	4.94	4.05
Bridge	1, 2,3,4,5	0	0	0	0	0	0
			1	0	0	1.23	0.33
			2	0	0	4.94	2.26
	3	1	1	20’000	2’100	1.23	0.33
			2	24’000	25’200	4.94	2.26
	4	2	1	30’000	2’800	1.23	0.33
			2	36’000	4’400	4.94	2.26
	5	3	1	40’000	3’500	1.23	0.33
			2	48’000	4’200	4.94	2.26

Table 9: Differences of traffic configuration

Road type			Object	Traffic configuration	
Description	Number of normal lanes	Number of emergency lanes		1	2
Highway	4	2	Road section	4-0	H2-N2
			Bridge	4-0	H2-N2
			Tunnel	4-0	H2-N2
		0	Road section	2-0	H2-N1
			Bridge	NA	NA
			Tunnel	2-0	H2-N1
Cantonal road	4	0	Road section	2-0	H2-N1
			Bridge	NA	NA
			Tunnel	NA	NA
	3	0	Road section	1-1	N1-N1
			Bridge	1-1	N1-N1
			Tunnel	1-1	N1-N1
	2	1	Road section	1-1	N1-N1
			Bridge	NA	NA
			Tunnel	NA	NA
	2	2	Road section	NA	NA
			Bridge	NA	NA
			Tunnel	NA	NA
Rural road	2	0	Road section	N2	1-0
	2	0	Bridge	NW	1-0
	2	0	Tunnel	NW	1-0
Mountain road	2	0	Road section	NW	1-0
	2	0	Bridge	NW	1-0
	2	0	Tunnel	NA	NA

Table 10: Types of traffic configurations

TC	Description
4-0	All three lanes of one direction are completely closed. One side is free of traffic which allows performing all interventions nearly undisturbed. The open side with its originally one emergency and two regular lanes is regrouped to four narrower lanes, two in each direction. Due to the missing emergency lanes and the smaller lane width the speed limit is reduced from 120 km/h to 80 km/h.
H2-N2	One lane at the time is closed on one side of the highway while the other side remains completely open. Within three steps the intervention for one travel direction can be completed. One third of the road is closed for work zones, two narrower lanes with lower speed limits (80 km/h) are used for traffic. Only one travel direction of the highway is affected but six instead of two steps are necessary to complete an intervention on the whole object.
2-0	One side of the road is closed for intervention while on the other side two lanes – one in each travel direction – are being operated.
H2-N1	This TC requires four steps to complete an intervention on the whole road. Two lanes in one travel direction remain untouched, in the other travel direction one lane is closed and the other remains open, but is slightly narrower than in regular operation.
1-1	Two lanes – one in both travel directions – remain open; the third lane provides the required space for the intervention.
N1-N1	Half of the road is closed. On one half the intervention takes place, on the other half two narrow lanes are installed. The speed limit is significantly lower than in the “1-1” setup due to the narrower lanes.
1-0	One lane remains open for the traffic in both travel directions; a traffic light system regulates the traffic flow.
N2	A third of the road is closed for intervention, two narrow lanes are installed on the remaining two third of the road.
NW	The whole intervention only takes place during the nighttime, during the day the road is completely open to the traffic. The works have to be divided in a way, that during daytime cars and trucks are still able to cross the intervention zone.

3.4 MODEL

The model of the intervention and traffic configurations for the partial network, where a node represents a possible intervention - traffic configuration combination for a road segment, is shown in Fig. 4. The node number are comprised of three parts (XXX.Y.Z). XXX indicates the physical road segment, Y indicates the intervention type, and ZZ indicates the traffic configuration.

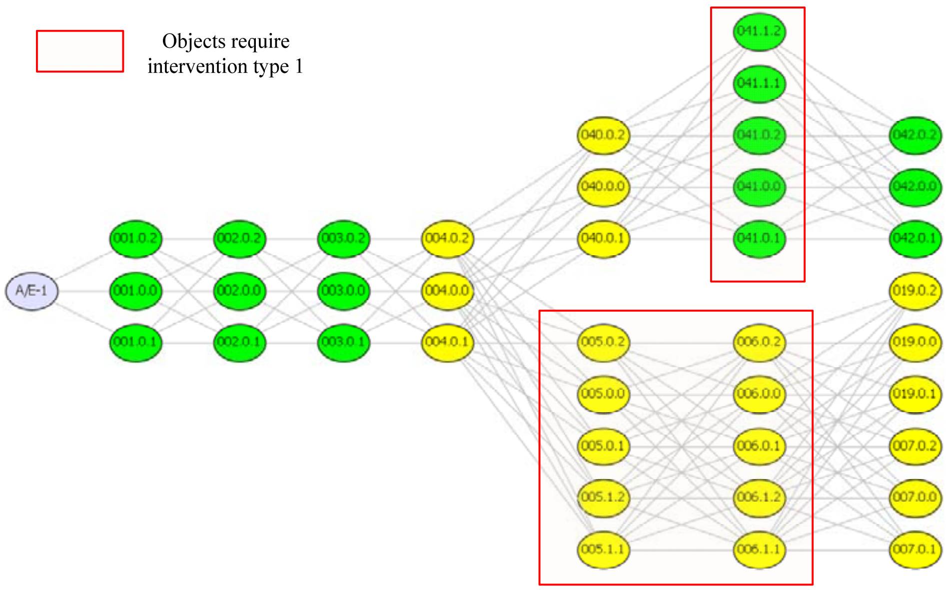


Fig. 4: Nodes and links representing the possible interventions and traffic configurations

For example, the Y = 0 in the node reference indicates an intervention of type 0 (which is equivalent to “do-nothing”), whilst, Y = 1 in the node reference (e.g. nodes with XXX = 005, 006 and 041) indicates an intervention of type 1 (refer to Table 5-Table 8).

3.5 SCENARIOS

In order to investigate the effect of budget and work zone length constraints, three scenarios were investigated (Table 11). The objective in each case was the same, i.e. to determine the OWZs.

Table 11: Descriptions of scenarios

Scenarios	Budget [x10^6. CHF]	L^{max} (km)
1	>= 74.4	15
2	>= 74.4	10
3	55.9	15

3.6 RESULTS

The optimal results for three scenarios were obtained after running the optimization models on each data set. A summary of the values of objective function, impacts incurred by the owner (agency cost is given in Table 12)

Table 12: Optimal values of impacts

Scenario	Total benefits [Mio. CHF]	Differences	Reduction %
1	370.46	0	0
2	349.16	21.3	-6
3	340.41	30.1	-8

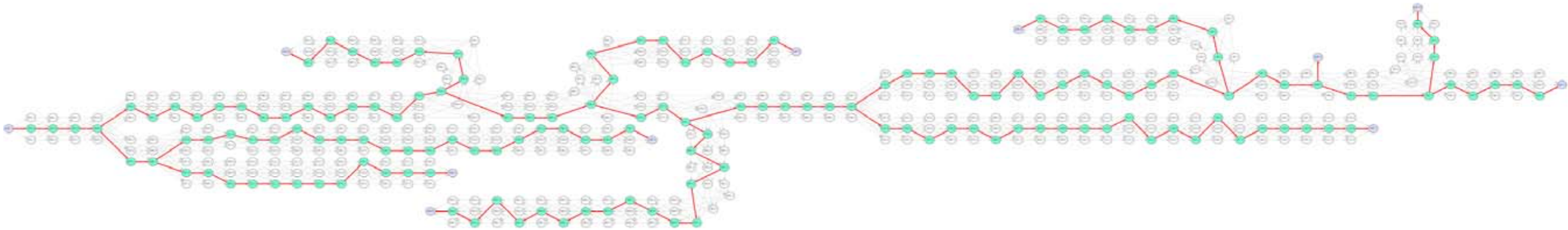
The OWZs for each scenario are shown graphically in Fig. 5. This figure simplifies the graph in Fig. 4 by representing only the possible traffic configurations for each object, i.e. it is possible to tell that an intervention is to be executed but not which type of intervention.

In the figure, the red line indicates the traffic configuration over the length of the entire network. The differences between the graphs are emphasized by coloring the nodes in different colors (pink for scenario 2 and purple in scenario 3) that are different in comparison with those for scenario 1. A detail of how a work zone is different for each scenario is further illustrated in Fig. 6, Fig. 7, and Fig. 8.

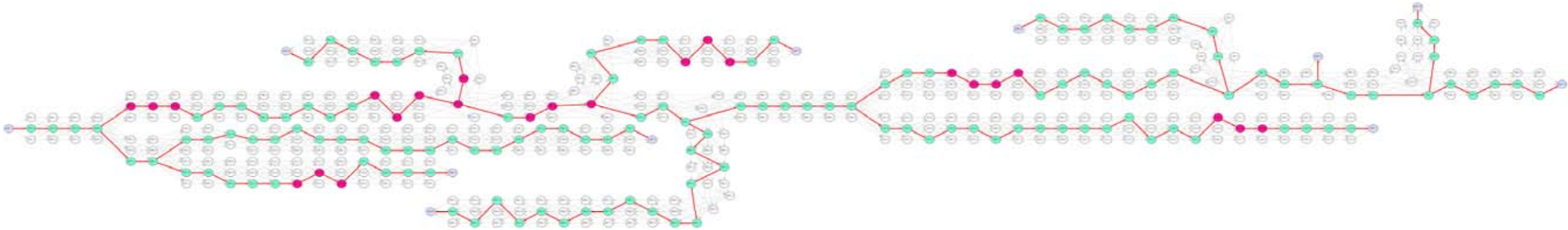
Under scenario 1, where the budget is equal or greater than 74.4 million CHF and the maximum length of work zone is 15 km, the expected total benefit is 370.46 million CHF. When the maximum length constraint is reduced from 15 km to 10 km (scenario 2), while having the same budget constraint as in scenario 1, the OWZs are no longer the same as those in scenario 1. For example, object 041 is no longer included in the OWZs (Fig. 7). It can also be seen that the reduction in the length constraint results in a reduction in expected total benefit, in this case, 6%.

The reduction of budget from 25% of that in scenario 1 (scenario 3) results an expected total benefit of 340.41 million CHF, which is 8% lower than that of scenario 1. By comparing the OWZs for both scenarios (Fig. 8), the changes in the objects to have interventions can be seen. For example, object 006 is no longer included in a work zone due to the tighter budget restrictions.

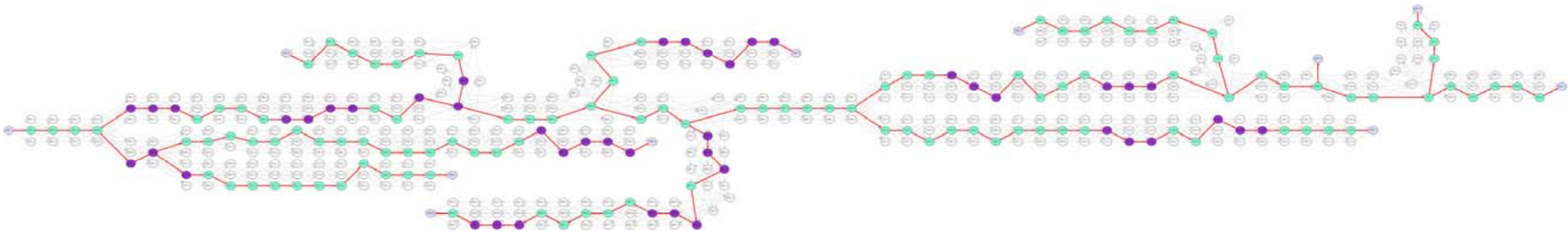
a-Scenario 1



b-Scenario 2



c-Scenario 3



Note: If the nodes belong to one object go vertically; the middle node represents “IS0- TC0”, the upper and lower node infer YY-TC2 and IS.YY.TC1, respectively.
If the nodes belong to one object go horizontally; the middle node represent “IS0- TC0”, the right and left node infer YY-TC2 and YY-TC1, respectively.
YY represent intervention type on actual condition state of the object (Table 5-Table 8)

Fig. 5: Graphical representation of optimal solutions under SC1, SC2, and SC3

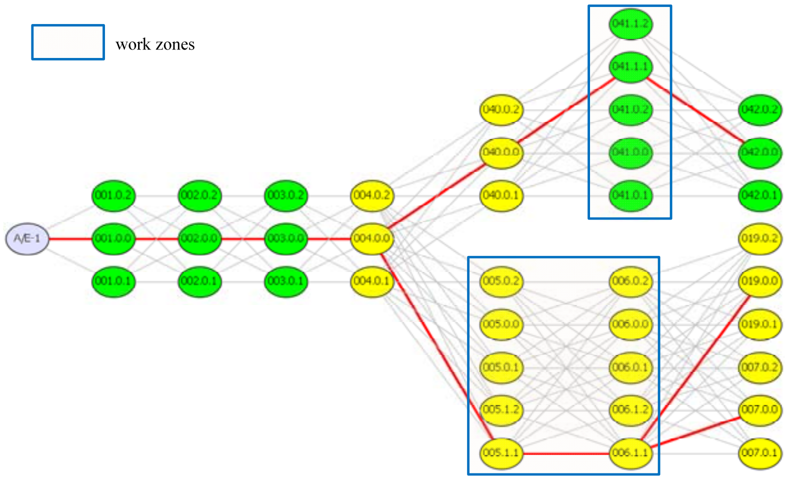


Fig. 6: Optimal work zone - scenario 1

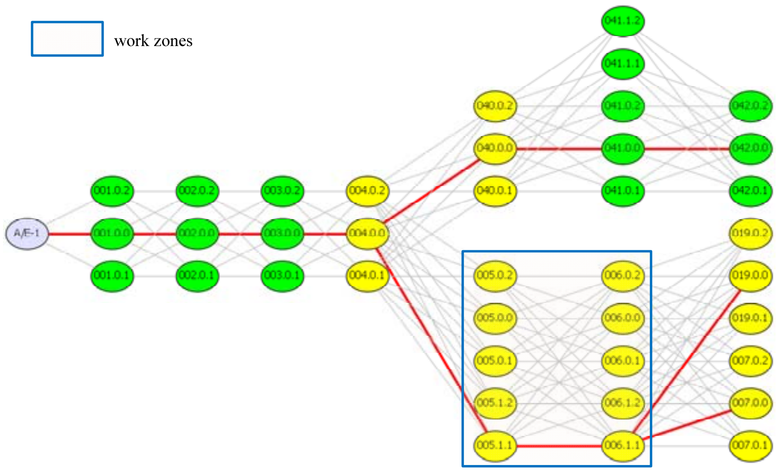


Fig. 7: Optimal work zone - scenario 2

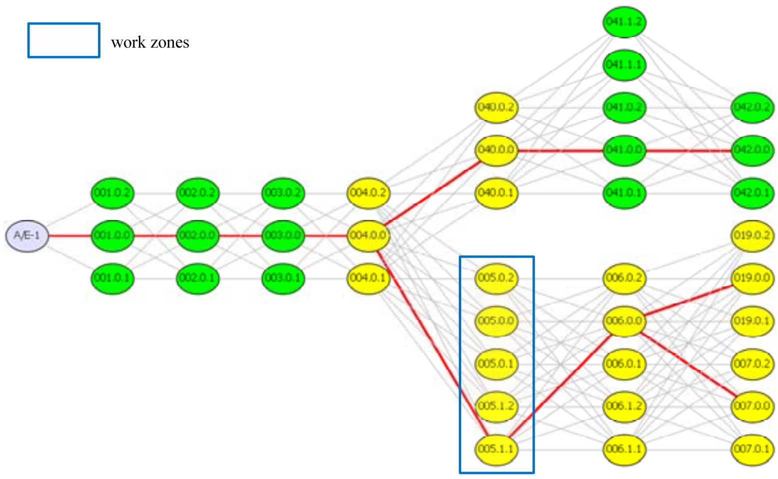


Fig. 8: Optimal work zone - scenario 3

4 CONCLUSION

In this paper a linear mixed integer optimization model to be used for determination of optimal work zones for a transportation network composed of a large number of infrastructure objects has been proposed. It can be used along with variations in the right hand side of the constraints, to determine the optimal grouping of interventions in work zones and the optimal traffic configurations to be used through these work zones. The model was tested on an example transportation network consisting of 160 infrastructure objects, with different characteristics (bridges, tunnels, and road sections).

Future study is required to extend the model to deal with more complex networks, multiple planning periods and to introduce distance constraints between work zones.

5 REFERENCES

[1] B. F. Kallas, "Pavement maintenance and rehabilitation," 1985.

[2] B. Adey, A. A. Khaled, M. M. Maher, P. L. Durango-Cohen, R. Guido, H. Rade, A. Bryan, B. Eugen, C.-Y. Y. Chu, D. M. Frangopol, M. J. Kallen, J. M. V Noortwijk, G. Roelfstra, R. Hajdin, E. Brühwiler, and J. O. Sobanjo, "Probabilistic Models for Life-Cycle Performance of Deterioration Structures: Review and Future Directions," *ASCE Conf. Infrastruct. Manag. Plan.*, vol. 6, no. 1, pp. 17–32, Feb. 2004.

[3] Y. Wang, R. L. Cheu, and T. F. Fwa, "Highway maintenance scheduling using genetic algorithm with microscopic traffic simulation," in *Proceeding of TRB 81st Annual Meeting*, 2002.

[4] B. Adey, T. Herrmann, K. Tsafatinos, J. Luking, N. Schindele, and R. Hajdin, "Methodology and base cost models to determine the total benefits of preservation interventions on road sections in Switzerland," *Struct. Infrastruct. Eng. Maintenance, Manag. Life-Cycle Des. Perform.*, vol. 8, no. 7, pp. 639–654, 2010.

[5] A. Ferreira, L. Picado-Santos, and A. Antunes, "A Segment-linked Optimization Model for Deterministic Pavement Management Systems," *Int. J. Pavement Eng.*, vol. 3, no. 2, pp. 95–105, 2002.

[6] N. Sathaye and S. Madanat, "A bottom-up solution for the multi-facility optimal pavement resurfacing problem," *Transp. Res. Part B Methodol.*, vol. 45, no. 7, pp. 1004–1017, Aug. 2011.

[7] R. Hajdin and H. P. Lindenmann, "Algorithm for the Planning of Optimum Highway Work Zones," *J. Infrastruct. Syst.*, vol. 13, no. 3, pp. 202–214, 2007.

[8] ERA-NET, "Stakeholders Benefits and Road Interventions Strategies," 2012.

[9] C. H. Chen, P. Schonfeld, and J. Paracha, "Work zone optimization for two-lane highway resurfacing projects with an alternate route," *Transp. Res. Rec.*, vol. 1911, pp. 51–66, 2005.

[10] Y. Chang, O. B. Sawaya, and A. K. Ziliaskopoulos, "A Tabu Search Based Approach for Work Zone Scheduling," in *Proceeding of the TRB 80th Annual Meeting*, 2000, no. 01–2950.

[11] ASTRA, *Forschungspaket Massnahmenplanung im EM von Fahrbahnen. Standartisierte Erhaltungsmassnahmen*. Federal Roads Office, Switzerland, 2008.