Effect of Common Cause Failures on Indirect Costs

Bryan Adey[1]; Rade Hajdin[2]; and Eugen Brühwiler[3]

Abstract: Next generation bridge management systems will take into consideration multiple hazard scenarios and not only traffic loading and structural deterioration as they do now. The indirect costs used in these bridge management systems to determine optimal management strategies vary according to the hazard scenarios considered. The difference depends on whether or not the bridge failures are due to a common cause, such as a single flood or earthquake, or due to load events that may be considered statistically unrelated, such as truck loads. To illustrate the effect of common cause bridge failures on indirect costs, two examples are presented that treat the failures first as if they are due to statistically independent loading events and then as if they are due to a common cause. To examine the effect of bridge failures on indirect costs of the system, estimation is performed at the network level. The first example, on a simple network, shows the indirect cost estimate for all of the network condition states. The second example, on a complex network, shows the difference in the possible reduction of total indirect costs with a single bridge intervention as well as the change in intervention sequence. The main conclusions are that total indirect costs and optimal intervention sequences differ depending on whether or not bridge failures are due to a common cause, and that the largest changes in indirect cost estimation occur when simultaneously failed bridges affect the method of indirect cost incurrence.

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Introduction

The optimal allocation of resources within an infrastructure network is becoming an increasingly prevalent problem. In recent years bridge management systems (BMSs), such as Pontis, Bridgit, and Kuba-MS (Cambridge Systematics 1997; National Engineering Technology Corporation 1998; Ludescher and Hajdin 1998), have been developed to help engineers and decision makers evaluate multiple intervention options and maximize potential benefits using limited resources. These potential benefits include savings in both direct and indirect costs. Direct costs are those incurred by the infrastructure owner, such as material and labor costs incurred by undertaking an action, like a deck replacement or rehabilitation. Indirect costs are those incurred by users of the infrastructure network, such as travel time and vehicle operating costs.

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Currently, when estimating direct and indirect costs in BMSs only the condition of the bridge being investigated is considered. The condition of the state of the other bridges in the network, i.e., the network condition state, is not considered. Although this is acceptable for estimation of direct costs, it is questionable for indirect costs. The indirect costs of bypassing a nonoperational bridge depend not only on the individual structure but also on the condition of the network. The accuracy of the indirect cost approximation therefore depends on the probability of having all other bridges operational simultaneously.

If the probabilities of simultaneously failed bridges are negligible, then both direct and indirect costs can be accurately estimated assuming that all other bridges in the network are operational. If the probability of simultaneously failed bridges is not negligible, however, as is the case when bridge failures are due to a common cause, such as floods and earthquakes, this assumption cannot be made. Indirect costs must then be estimated taking into consideration the probability of simultaneous failed bridges as well as the network connectivity and functionality.

Next generation BMSs will attempt to optimize resource allocation in bridge networks by taking into consideration multiple hazard scenarios, and not only traffic load as they do now. Once multiple hazard scenarios are considered in the search for the optimal resource allocation, common cause failures must be considered (Adey et al. 2001).

In this paper, using two examples, we show the potential significance of the consideration of common cause bridge failures on the estimation of indirect costs. The first example uses a simple network, one source and one destination node. The additional indirect costs and their probability of occurrence are determined for each of the network condition states. The second example uses a complex network, multiple source and destination nodes, and shows the change in the possible reduction of total indirect costs with a single intervention and the resulting difference in the optimal intervention sequence. The indirect costs are estimated for both examples assuming the probability of simultaneous failures is negligible and then assuming that it is not negligible. The effect on optimal resource allocation is shown.

Failure Categories

Two categories of bridge failure are considered in a network: (1) bridge failures where at the time of failure it **may** be assumed that all other bridges are operational, i.e., the probability of more than one failed bridge in the network at a time is negligible, and (2) bridge failures where at the time of failure it **may not** be assumed that all other bridges are operational at the same time, i.e., the probability of more than one failed bridge in the network at a time is not negligible. Bridge resistances are assumed to be statistically independent in both categories. The indirect costs associated with these failure categories can differ significantly and can result in different management strategies.

Bridge failures where, at the time of failure, it may be assumed that all other bridges are operational occur due to loading events that may be treated as statistically independent (assuming sufficiently short repair times), e.g., traffic loading. Since the action effects due to traffic loading are not temporally correlated the probability of simultaneously failed bridges is negligible. Bridge failures where, at the time of failure, it may not be assumed that all other bridges are operational are those that are due to a common cause, e.g., a flood. Bridges on the same river system are frequently subjected to flooding, and therefore extreme flooding, simultaneously. Because there is an almost perfect temporal correlation between flood actions, the probability of simultaneously failed bridges due to flooding is not negligible.

Indirect Costs

The indirect costs related to an infrastructure network can be divided into two categories: (1) those associated with temporal prolongation of travel, and (2) those associated with the loss of connectivity. In extreme cases of temporal travel prolongation (due to long detours or congestion), the indirect costs approach the values attained with the loss of connectivity, i.e., a more time consuming journey can turn prohibitive for portions of commercial and individual traffic. These extreme cases are not considered in this paper. Although this assumption eliminating the extreme cases may not be correct in the real world, it is made to simplify the example and does not detract from the validity of the arguments presented.

Indirect costs associated with prolongation of travel are most important when a network is highly redundant (there is little chance of connection loss). In highly redundant networks with adequate traffic capacity even with the closure or loss of one or two links between cities, detours are possible. Indirect costs are therefore due to such things as additional travel time, vehicle operating costs and increased risk of accidents. Indirect costs associated with the loss of connectivity are most important when a network has low redundancy (the chance of connection loss is not negligible). These indirect costs are due to the loss of economic activity that occurs while travel is not possible. The total indirect costs incurred on an infrastructure network are comprised of both categories. The magnitude of each depends on the network characteristics.

Total Additional Indirect Costs

In determination of optimal management strategies for bridges in the network, it is the total additional indirect costs incurred for the network that are of interest. To determine these total additional indirect costs, the indirect costs that would be incurred by the users when the network is in each of the likely network condition states (NCSs) must be estimated. All possible NCSs can be thought of as sample space, *S*, and since sample space has a finite number of elements (NCSs), they may be written as

$$S=\{\mathrm{NCS}_0,\mathrm{NCS}_1,\ldots,\mathrm{NCS}_n\} \tag{1}$$

where $0=$ fully operational NCS and $n=$ total number of NCSs.

Each NCS describes one and only one combination of failed and fully operational bridges in the network. Since the sample points are considered as collectively exhaustive, i.e., the network may be represented using one of these NCSs, the total additional indirect costs ($\mathrm{AIC}_{\mathrm{tot}}$) incurred for an infrastructure network are the sum of the additional indirect costs that would be incurred if the network were in each of the damaged NCSs, $\mathrm{AIC}_{\mathrm{NCS}i}$, multiplied by the probability of occurrence of the network being in each NCS, $P_{\mathrm{NCS}i}$. A damaged NCS is defined as a NCS that is not fully operational, i.e., there is at least one link that is not operational.

$$\mathrm{AIC}_{\mathrm{tot}}=\sum_{i=1}^{n}\left[\mathrm{AIC}_{\mathrm{NCS}i}\cdot P_{\mathrm{NCS}i}\right] \tag{2}$$

where i indicates the NCS.

Additional Indirect Costs in Network Condition States

The additional indirect costs incurred when the network is in each NCS, $\mathrm{AIC}_{\mathrm{NCS}i}$, = indirect costs incurred when the network is in that NCS, $C_{\mathrm{NCS}i}$, minus the indirect costs incurred when the network is fully operational, C_{NCS0}

$$\mathrm{AIC}_{\mathrm{NCS}i}=C_{\mathrm{NCS}i}-C_{\mathrm{NCS0}} \tag{3}$$

The following parameters are used to estimate the additional indirect costs when the network is in a NCS:

- Number of vehicles on the links, ν_l;
- Length of the links, d_l;
- Length of the detours, d_d;
- Cost per vehicle kilometer of travel, CVK;
- Cost per vehicle per day if travel is not possible, CV;
- Number of days until repair of the links, DUR_l.

If there is no loss of connectivity, the additional indirect costs are due to prolonged travel.

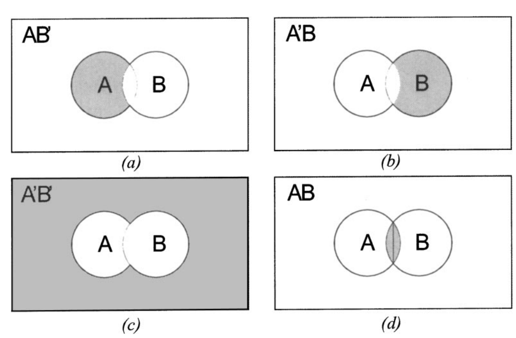

Fig. 1. Venn diagrams of the intersection of bridge failures creating the NCSs: (a) NCS-A intersection of A and B′, (b) NCS-B intersection of A′ and B′, (c) NCS-0 intersection of A′ and B′, and (d) NCS-A/B intersection of A and B

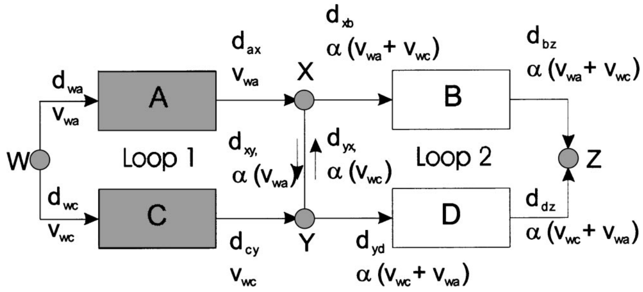

Fig. 2. Simple bridge network

$$\mathrm{AIC}=(d_d-d_l)\cdot \nu_l\cdot CVK\cdot DUR_l \tag{4}$$

Although there are variations (Watanatada et al. 1987), it is assumed in this paper, that vehicles travel at one constant speed on all roads and that the vehicle operating costs per kilometer of travel remains the same regardless of the link traveled. Assumptions must be made with respect to user behavior following link failure and the intervention sequence if multiple links have failed.

If there is connection loss, additional indirect costs result due to the loss of economic activity. In reality the loss of economic activity is more complex than this linear approximation but the economic impact of link closure is beyond the scope of this study.

$$\mathrm{AIC}=(\nu_l\cdot CV-d_l\cdot \nu_l\cdot CVK)\cdot DUR_l \tag{5}$$

The additional indirect costs related to a NCS are represented by an equation set. The number of equations in each set corresponds with the number of NCSs the network must pass through before it is restored to the fully operational network condition state. For example, additional indirect costs incurred for a network with a single failed link are represented by a single equation [as in Eqs. (4) and (5)] because the network is in only one damaged state prior to being restored to the fully operational NCS. The additional indirect costs incurred for a network with two failed links (assuming only one link is repaired at a time), are represented by two equations because the network will be in two damaged states prior to being restored to the fully operational NCS.

Table 1. Simple Network: Link Lengths and AADT

Link	Length	AADT	Link	Length	AADT
d_{wa}	10	10	d_{xy}	10	5
d_{wc}	10	10	d_{yx}	10	5
d_{ax}	10	10	d_{yd}	10	10
d_{cy}	10	10	d_{bz}	10	10
d_{xb}	10	10	d_{dz}	10	10

Probability of Occurrence of Network Condition States

The probability of occurrence of each NCS, P_{NCS}, is the probability of having the required combination of operational and non-operational links in the NCS. Using Venn diagrams this is represented as the intersection of the events required (link failure) and complementary events (link survival).

The NCSs for a two link network are illustrated in Fig. 1. Each event, A and B (failure of links A and B, respectively), is illustrated using circles. Each complementary event, A′ and B′ (survival of links A and B, respectively), includes everything in sample space outside of their respective events.

Fig. 1(a) is NCS-A where link A has failed and link B has survived, i.e., it is the intersection of event A (failure of link A) and complementary event B′ (survival of link B). Fig. 1(b) is NCS-B, the intersection of event B (failure of link B) and complementary event A′ (survival of link A). Fig. 1(c) is NCS-0, the intersection of the complementary event A′ (survival of link A) and complementary event B′ (survival of link B). Fig. 1(d) is NCS-A/B, the intersection of event A (failure of link A) and event B (failure of link B). The probability of each event is assumed to be statistically independent.

Simple Network: One Source and One Destination Node

To illustrate the potential significance of consideration of common cause failures and network connectivity on estimation of additional indirect costs, the indirect costs for a simple network (Fig. 2), with one source and one destination node, are

Table 2. Simple Network: Indirect Cost Formulations for Network Condition States (NCSs)

Indirect cost formulations — Eq.

$$IC_0=\{[(d_{wa}+d_{ax})\cdot\nu_{wa}+(d_{wc}+d_{cy})\cdot\nu_{wc}+(d_{xb}+d_{bz}+d_{xy}+d_{yd}+d_{dz})\cdot(\nu_{wa}+\nu_{wc})\cdot\alpha]\cdot CVK\cdot DUR\quad \text{NCS-0}\} \tag{7}$$

$$IC_a=\{[(d_{wc}+d_{cy})\cdot(\nu_{wa}+\nu_{wc})+(d_{yd}+d_{dz}+d_{yx}+d_{xb}+d_{bz})\cdot[\alpha\cdot(\nu_{wa}+\nu_{wc})]]\cdot CVK\cdot DUR_a\quad \text{NCS-A}\} \tag{8}$$

$$IC_{ab}=\left\{\begin{array}{lr} (d_{wc}+d_{cy}+d_{yd}+d_{dz})\cdot(\nu_{wa}+\nu_{wc})\cdot CVK\cdot DUR & \text{NCS-A/B}\\ [(d_{wa}+d_{ax}+d_{xy})\cdot\nu_{wa}+(d_{wc}+d_{cy})\cdot\nu_{wc}+(d_{yd}+d_{dz})\cdot(\nu_{wa}+\nu_{wc})]\cdot CVK\cdot DUR & \text{NCS-B}\end{array}\right\} \tag{9}$$

$$IC_{ac}=\left\{\begin{array}{lr} (\nu_{wa}+\nu_{wc})\cdot CV\cdot DUR_a & \text{NCS-A/C}\\ [(d_{wa}+d_{ax})\cdot(\nu_{wa}+\nu_{wc})+(d_{xb}+d_{bz}+d_{yx}+d_{xb}+d_{bz})\cdot[\alpha\cdot(\nu_{wa}+\nu_{wc})]]\cdot CVK\cdot DUR_c & \text{NCS-C}\end{array}\right\} \tag{10}$$

$$IC_{abc}=\left\{\begin{array}{lr} (\nu_{wa}+\nu_{wc})\cdot CV\cdot DUR_c & \text{NCS-A/B/C}\\ (d_{wc}+d_{cy}+d_{yd}+d_{dz})\cdot(\nu_{wa}+\nu_{wc})\cdot CVK\cdot DUR_a & \text{NCS-A/B}\\ [(d_{wc}+d_{ax}+d_{xy})\cdot\nu_{wa}+(d_{wc}+d_{cy})\cdot\nu_{wc}+(d_{yd}+d_{dz})\cdot(\nu_{wa}+\nu_{wc})]\cdot CVK\cdot DUR_b & \text{NCS-B}\end{array}\right\} \tag{11}$$

$$IC_{abcd}=\left\{\begin{array}{lr} (\nu_{wa}+\nu_{wc})\cdot CV\cdot DUR_a & \text{NCS-A/B/C/D}\\ (\nu_{wa}+\nu_{wc})\cdot CV\cdot DUR_b & \text{NCS-B/C/D}\\ [(d_{wa}+d_{ax}+d_{xb}+d_{bz})\cdot(\nu_{wa}+\nu_{wc})]\cdot CVK\cdot DUR_c & \text{NCS-C/D}\\ [(d_{wc}+d_{cy}+d_{yx})\cdot\nu_{wc}+(d_{wa}+d_{ax})\cdot\nu_{wa}+(d_{xb}+d_{bz})\cdot(\nu_{wa}+\nu_{wc})]\cdot CVK\cdot DUR_d & \text{NCS-D}\end{array}\right\} \tag{12}$$

Table 3. Simple Network: Probability of Occurrence of Damaged Network Condition States (NCSs)

NCS	Probability of occurrence	Eq.
A	$\mathbf{A_F \cdot B_S \cdot C_S \cdot D_S}$	**(13)**
AB	$A_F \cdot B_F \cdot C_S \cdot D_S$	(14)
AC	$A_F \cdot B_S \cdot C_F \cdot D_S$	(15)
ABC	$A_F \cdot B_F \cdot C_F \cdot D_S$	(16)
ABCD	$A_F \cdot B_F \cdot C_F \cdot D_F$	(17)

estimated. It is assumed that link failure is the result of bridge failure.

Network Characteristics

In the simple network (Fig. 2), the bridges are treated as nodes. The source node, destination node and intersection nodes are indicated by circles (W,X,Y,Z). The bridge nodes are indicated by rectangles (A,B,C,D). The distances between nodes (the link lengths) are denoted d_{ij} (i is the start node and j is the end node).

It is assumed that traffic flow through the network for all NCSs is known. The number of vehicles on each link is denoted v_{ij}. All traffic travels from W, the source node, to Z, the destination node. Incoming traffic at node X from bridge A bifurcates into two flows, each consisting of a fraction α of the incoming flow. One of these flows then passes over bridge B and the other passes over bridge D, en route to the destination node Z. At node Y the incoming traffic from bridge C bifurcates into two flows, each consisting of a fraction α of the incoming flow. One of these flows then passes over bridge B en route to the destination node, Z, and the other passes over bridge D, en route to destination node Z. Link lengths and traffic volumes are given in Table 1.
The NCSs are as follows:

$$S=\{0,A,B,C,D,AB,CD,AD,BC,AC,BD,$$
$$ABC,ACD,ABD,BCD,ABCD\} \tag{6}$$

where sample point 0 (zero) corresponds to the fully operational NCS and the others represent the damaged NCS, with the letters representing failed bridges.

Additional Indirect Costs in Network Condition States

The indirect costs that would be incurred for the network in the fully operational NCS and five damaged NCSs that represent the different indirect cost formulations are shown in Table 2. It is assumed that there is only one bridge intervention at a time and that the intervention sequence is known.

When two bridge failures do not result in connection loss (AB, AD, BC, CD) it is assumed that the bridge closest to destination node Z is repaired first. When bridge failures result in connection loss (AC, BD, ABC, ABD, BCD, and ABCD) it is assumed that the bridge (or bridges) that restores the connection will be repaired first. If all bridges fail it is assumed that bridge B will be repaired first and then bridge A.

Probability of Occurrence of Network Condition States

The probability of occurrence for each of the damaged NCSs is given in Table 3. The probability of occurrence of damaged NCS-A is illustrated using an event tree analogy in Fig. 3 and reads as follows:

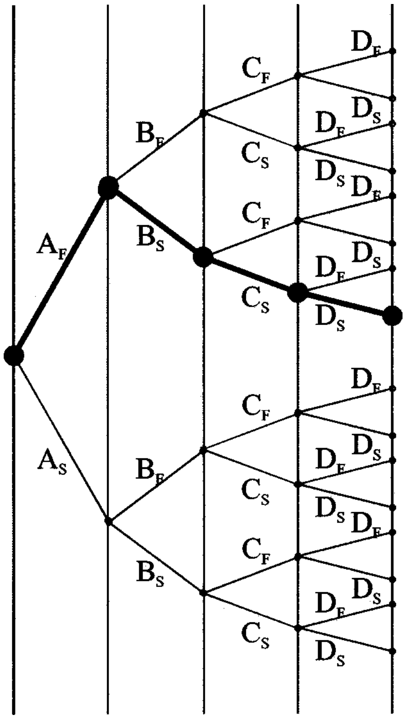

Fig. 3. Event tree analogy: probability of failure or survival of each bridge in simple network (NCS-A shown in bold face)

The probability that bridge A has failed, A_F, multiplied by the probability that bridge B has survived, B_S, multiplied by the probability that bridge C has survived, C_S, multiplied by the probability that bridge D has survived, D_S.

Numerical Example

The additional indirect costs associated with each NCS in the simple network are first estimated assuming that the probability of simultaneous failures is negligible and then assuming that it is not negligible. The link lengths and the traffic volume given in Table 1, a ratio of CVK/CV of 0.0001 and a DUR of 30 days, are used. The probability of failure for each bridge is given in Table 4. The probability of failure of bridges A and C is assumed to be identical, although statistically independent. Bridges B and D were assumed not to fail. If the probability of simultaneous failure is assumed to be negligible, then only the probability of failure printed in bold face in Table 4 (on the diagonal), is used and all other probability of failure $=0$. If the probability of simultaneous failure is not assumed to be negligible then all probabilities of failure given in the matrix are used. The possible NCSs under consideration are

$$S=\{0,A,C,AC\} \tag{18}$$

Table 4. Simple Network: Probability of Failure

Bridge	A	B	C	D
A	**0.1**		0.1	
B				
C	0.1		**0.1**	
D				

Table 5. Simple Network Indirect Costs

NCS	Probability of occurrence			Additional indirect costs
	Eq.	Mutually exclusive	Not mutually exclusive	
A	$A_F B_S C_S D_S$	$=(0.1)\cdot(1-0)\cdot(1-0)\cdot(1-0)$ $=0.1\cdot 1\cdot 1\cdot 1$ $=0.1$	$=(0.1)\cdot(1-0)\cdot(1-0.1)\cdot(1-0)$ $=0.1\cdot 1\cdot 0.9\cdot 1$ $=0.09$	$\text{AIC}_a = IC_a - IC_0$
C	$A_S B_S C_F D_S$	$=(1-0)\cdot(1-0)\cdot(0.1)\cdot(1-0)$ $=1\cdot 1\cdot 0.1\cdot 1$ $=0.1$	$=(1-0.1)\cdot(1-0)\cdot(0.1)\cdot(1-0)$ $=0.9\cdot 1\cdot 0.1\cdot 1$ $=0.09$	$\text{AIC}_c = IC_c - IC_0$
AC	$A_F B_S C_F D_S$	$=(0.1)\cdot(1-0)\cdot(1-1)\cdot(1-0)$ $=1\cdot 1\cdot 0\cdot 1$ $=0$	$=(0.1)\cdot(1-0)\cdot(0.1)\cdot(1-0)$ $=0.1\cdot 1\cdot 0.1\cdot 1$ $=0.01$	$\text{AIC}_{ac} = IC_{ac} - IC_0$

An estimate of the probability of occurrence for each NCS, as well as associated additional indirect costs, is shown in Table 5.

If the probability of simultaneous failure of bridges A and C is assumed to be negligible then there are no additional indirect costs due to bridge failure. This is because AIC_a and $\text{AIC}_c = 0$ and the probability of both bridges being nonoperational, NCS-A/C, is neglected:

$$\text{AIC}_{\text{tot}} = \text{AIC}_a \cdot P_a + \text{AIC}_C \cdot P_c + \text{AIC}_{ac} \cdot P_{ac}$$

$$\text{AIC}_{\text{tot}} = 0 \cdot P_a + O \cdot P_c + \text{AIC}_{ac} \cdot 0 \qquad (19)$$

$$\text{AIC}_{\text{tot}} = 0$$

AIC_a and $\text{AIC}_c = 0$ because the indirect costs associated with NCS-A and NCS-C are exactly the same as those associated with NCS-0. The indirect costs do not change because in both cases the detours are exactly the same length as the original routes, the CV/CVK ratios are the same and sufficient traffic capacity was assumed for both routes.

If the failure of bridges A and C is due to a common cause, i.e., the probability of simultaneous failures cannot be neglected, then although AIC_a and AIC_c are still $=0$, there are costs associated with NCS-A/C. When the network is in NCS-A/C, indirect costs are incurred until the connection between the source and destination node is restored.

$$\text{AIC}_{\text{tot}} = \text{AIC}_a \cdot P_a + \text{AIC}_C \cdot P_c + \text{AIC}_{ac} \cdot P_{\text{ac}}$$

$$\text{AIC}_{\text{tot}} = 0 \cdot P_a + 0 \cdot P_c + \text{AIC}_{ac} \cdot 0.01$$

$$\text{AIC}_{\text{tot}} = 0.01 \cdot \text{AIC}_{ac} \qquad (20)$$

For the simple network, the difference in AIC_{tot}, between assuming the probability of simultaneous failure are negligible and not negligible, is the omission or inclusion of the indirect costs in NCS-A/C (0 or 0.01 AIC_{ac}).

Complex Network: Multiple Source and Destination Nodes

To illustrate the impact that consideration of common cause failure may have on the optimal allocation of resources, the indirect costs of a real multinode network (Fig. 4), with multiple source and destination nodes, are estimated. An optimal allocation of resources is examined for both the case where the probability of simultaneous bridge failure is negligible and the case where it is not negligible. Again, it is assumed that link failure is the result of bridge failure.

Network Characteristics

The infrastructure network selected (Fig. 4) is in the Morogoro region of Tanzania. The total road network is 4,000 km of which 400 is paved and the rest is gravel and earth. The network was divided into 20 links and 19 nodes (Fig. 5). The probability of failure of each link is assumed to be that of one bridge along the link. The link lengths and traffic volume are given in Table 6.

It has been assumed that the traffic on a link must travel from the link start node to the link end node. For example, in Fig. 5 the thick solid line represents the desired path of a vehicle from Taweta to Mziha. If link Kilosa to Dumila-Magole has failed the

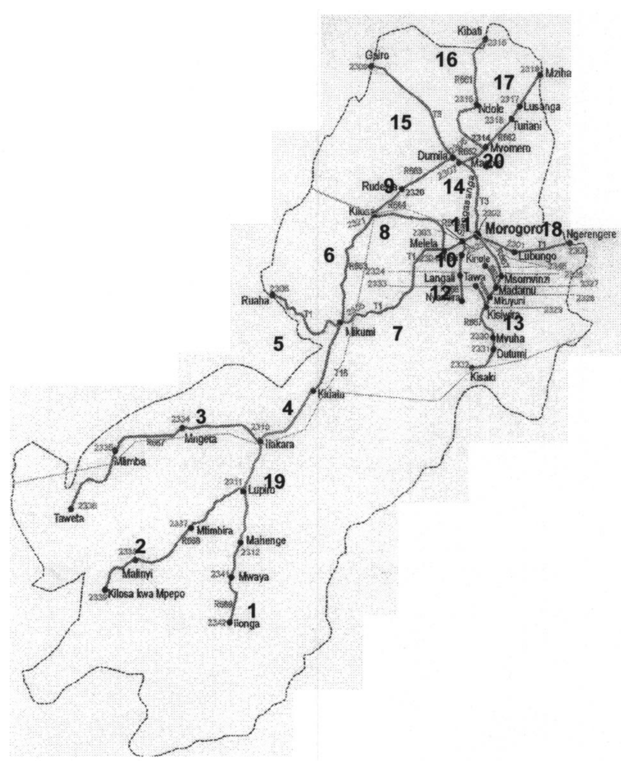

Fig. 4. Road network in the Morogoro region of Tanzania

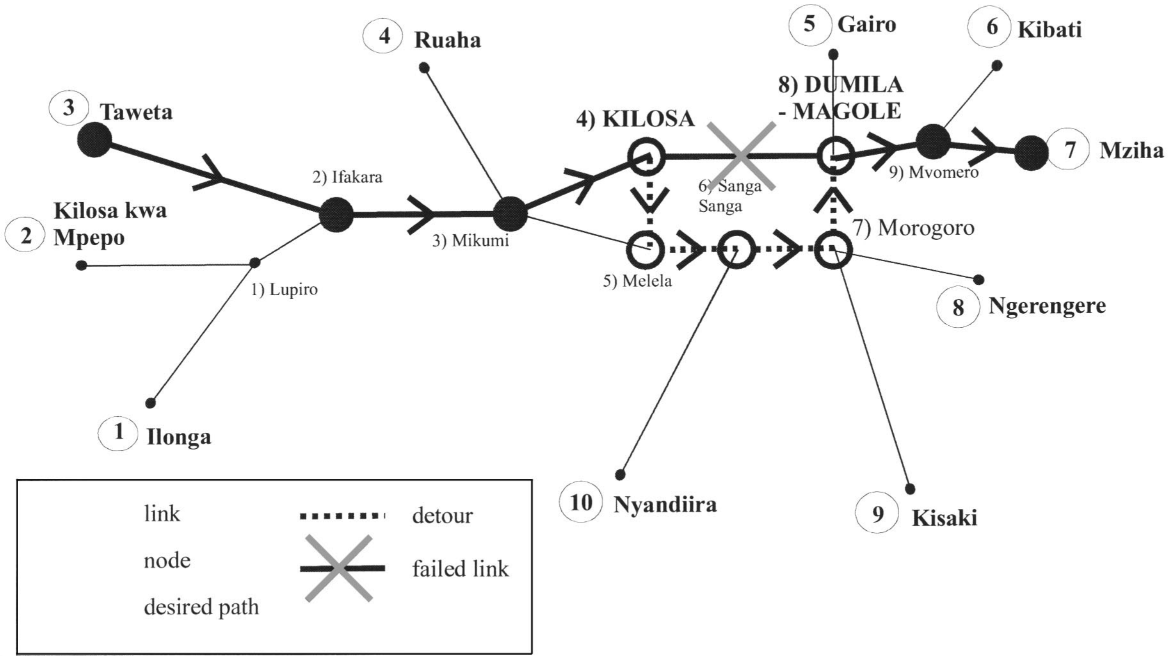

Fig. 5. Complex network: Traffic detour assumptions

vehicle must detour from Kilosa (the link start node) to Dumila-Magole (the link end node), along the dotted line shown, regardless of the final destination of the vehicle. More accurate modeling, using the start and destination nodes of each of the vehicles and their choice of alternate route when failure occurs (Augusti and Ciampoli 1997) is omitted. Further traffic flow modeling is beyond the scope of this study.

Only NCSs created by failure due to a common cause, namely, bridges that span the same river system, were considered. The probability of simultaneous failure of bridges over other river systems as assumed to be negligible. The simultaneous failures considered were links (11/18), (4/5/19), and (6/7/8/9/14). The NCSs considered, assumed to be collectively exhaustive, are as follows:

$$S=\left\{\begin{matrix}\phi,1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20\\(11/18),(4/5/19),(4/5),(4/19),(5/19)\\(6/7/8/9/14),(6/7),(6/8),(6/9),(6/14),(7/8),(7/9),(7/14),(8/9),(8/14),(9/14)\\(6/7/8),(6/7/9),(6/7/14),(6/8/9),(6/8/14),(6/9/14),(7/8/9),(7/8/14),(7/9/14),(8/9/14)\\(6/7/8/9),(6/7/8/14),(6/7/9/14),(6/8/9/14),(7/8/9/14)\end{matrix}\right\} \tag{21}$$

Table 6. Complex Network: Link Lengths and Average Annual Daily Traffic (AADT)

Link	Length (km)	AADT	Link	Length (km)	AADT
1	99	19	11	23	725
2	152	18	12	32	77
3	210	36	13	144	1,271
4	109	116	14	66	795
5	73	331	15	73	331
6	78	92	16	80	5
7	79	425	17	73	152
8	69	123	18	48	2,700
9	66	197	19	30	81
10	22	725	20	14	130

The additional indirect costs, AIC_{NCS}, and the probability of occurrence of NCSs, P_{NCS}, have been calculated as described for the simple network.

Numerical Example

The additional indirect costs incurred in each NCS considered in the complex network are estimated, and an optimal intervention sequence determined, assuming first that simultaneous failure cannot occur and second assuming that it can occur. A ratio of CVK/CV of 0.0001 and a DUR of 30 days are used. The assumed probability of failure for each bridge is given in Table 7 (read the same as Table 4). The NCSs are shown in Eq. (21).

Table 7. Complex Network: Probability of Failures

Link	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	**0.1**																			
2		**0.1**																		
3			**0.1**																	
4				**0.1**	0.1														0.1	
5				0.1	**0.1**														0.1	
6						**0.1**	0.1	0.1	0.1					0.1						
7						0.1	**0.1**	0.1	0.1					0.1						
8						0.1	0.1	**0.1**	0.1					0.1						
9						0.1	0.1	0.1	**0.1**					0.1						
10										**0.1**										
11											**0.1**							0.1		
12												**0.1**								
13													**0.1**							
14						0.1	0.1	0.1	0.1					**0.1**						
15															**0.1**					
16																**0.1**				
17																	**0.1**			
18											0.1							**0.1**		
19				0.1	0.1														**0.1**	
20																				**0.1**

Change in Magnitude of $AIC_{tot\ i}$

The additional indirect costs incurred for the network for each of the damaged NCSs, when the probability of simultaneous failures is assumed to be negligible and not negligible, are given in Fig. 6. The highest additional indirect costs, when the probability of simultaneous failure is assumed to be negligible, are incurred when the network is in NCS-18 (7.9), NCS-13 (3.5), and NCS-5 (0.96). The highest additional indirect costs, when the probability of simultaneous failure is not assumed to be negligible, are incurred when the network is in NCS-18 (7.1), NCS-13 (3.5) and NCS-15 (0.96).

The high additional indirect costs associated with NCS-18 and NCS-13, due to their high traffic volume, long length and the absence of alternate routes, mean that it is most beneficial to repair them regardless of whether or not simultaneous failure is considered. The change of NCSs, from NCS-5 to NCS-15, is due to the reduction in additional indirect costs associated with NCS-5. This reduction is due to a change in the probability of occurrence of NCS-5 (Fig. 7).

Figs. 7(a and b) illustrate graphically the probability of failure of links 4, 5 and 19 assuming that there is no probability of simultaneous failure and assuming that there is a probability of simultaneous failure, respectively. If the probability of simultaneous failure is negligible, the probability of failure of link 5 (within circle 5) = probability of occurrence of NCS-5 (shaded area). If the probability of simultaneous failure is not negligible

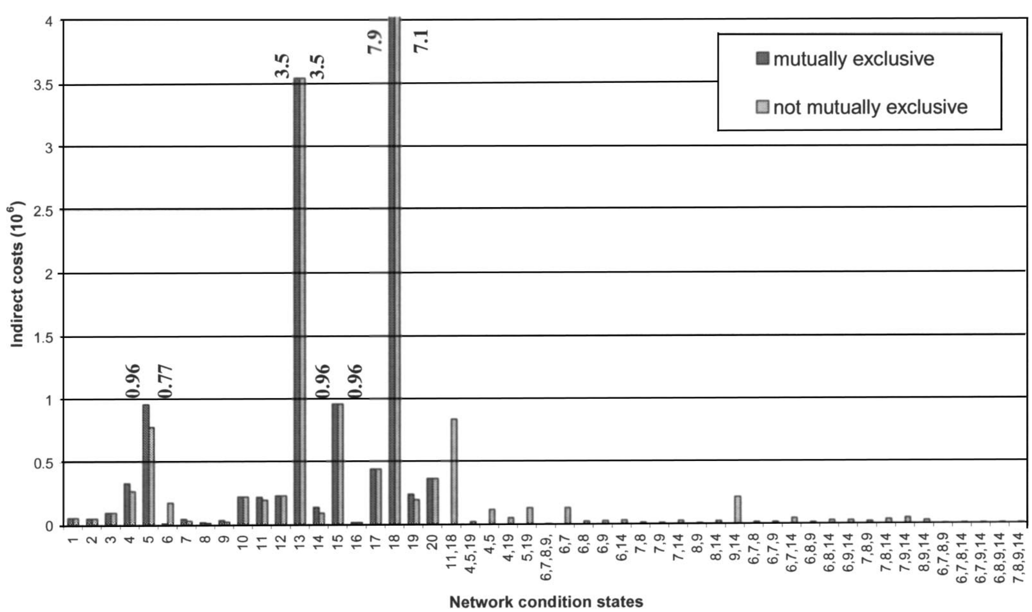

Fig. 6. Additional indirect costs for each network condition state

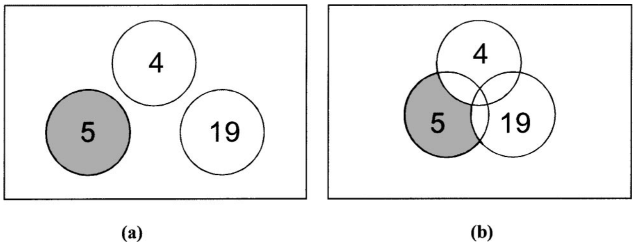

Fig. 7. Difference in probability assuming mutually exclusive and not mutually exclusive

the probability of failure of link 5 (0.1) is not equal to the probability of occurrence of NCS-5 (0.081). This difference reduces the additional indirect costs associated with NCS-5 from 0.96 to 0.77.

Possible Reduction in AIC_{tot} with Single Intervention

The predicted reductions in total additional indirect costs with a single intervention when the probability of simultaneous failure is assumed to be negligible and then not negligible are shown in Fig. 8. Only the links that are used in multiple NCSs are shown, e.g., link 5 is included in NCS-5, NCS-4/5, NCS-5/19 and NCS-4/5/19.

There is a slight increase in the possible reduction of additional indirect costs with an intervention on links, 4, 5, and 19, and 10 and 18, between assuming the probability of simultaneous failure is negligible and assuming that it is not. This slight increase is because if links fail simultaneously only one can be repaired at a time and additional indirect costs are incurred when the network is in the other damaged NCSs until the network is restored to fully operational NCS. The indirect costs associated with NCSs with multiple failures, in these cases, are not incurred differently than those associated with NCSs with single failures, i.e., the NCSs, with multiple failures (links 4, 5 and 19 or links 10 and 18) do not have longer detours or additional connectivity loss than the NCSs with only single failure.

There is a large difference in the possible reduction of additional indirect costs with interventions on links 6, 7, 8, 9 and 14, between assuming the probability of simultaneous failure is negligible and assuming that it is not. The indirect costs associated with NCSs with multiple failures, in this case, are incurred differently than those associated with NCSs with single failure, i.e., there are longer detours or additional connectivity loss associated with NCSs with multiple failures than with the NCSs with only single failure. For example, if link 6 alone fails (NCS-6) then the detour, links 7 and 8, is the minimum length. If, however, links 6 and 8 fail simultaneously (NCS-6/8), there will be larger detours than if just link 6 alone failed. The detour to drive from Mikumi to Kilosa would require links 7, 10, 11, 14 and 9. If links 6 and 7 failed simultaneously there would be a loss of connectivity that would not exist if only link 6 alone failed.

Intervention Sequence

Since the optimal allocation of resources is determined by minimizing the total direct and indirect costs incurred for an infrastructure network, changes in the possible reduction of additional indirect costs mean that optimal allocation of resources is altered. The intervention sequence, on the links presented in Fig. 8 if the probability of simultaneous failure is assumed to be negligible and only one intervention is possible, is 18, 5, 4, 19, 10, 14, 7, 9, 8 and 6. The intervention sequence, if the probability of simultaneous failure is assumed to be not negligible, is 18, 5, 14, 9, 6, 4, 7, 19, 10 and 8.

Regardless of whether or not the probability of simultaneous failure is assumed to be negligible, the largest reductions in additional indirect costs are possible with intervention on links 18 and 5 due to their high traffic volume, long lengths and absence of alternate routes.

If, however, intervention is not possible on links 18 and 5, and only one intervention can be made, then the consideration of com-

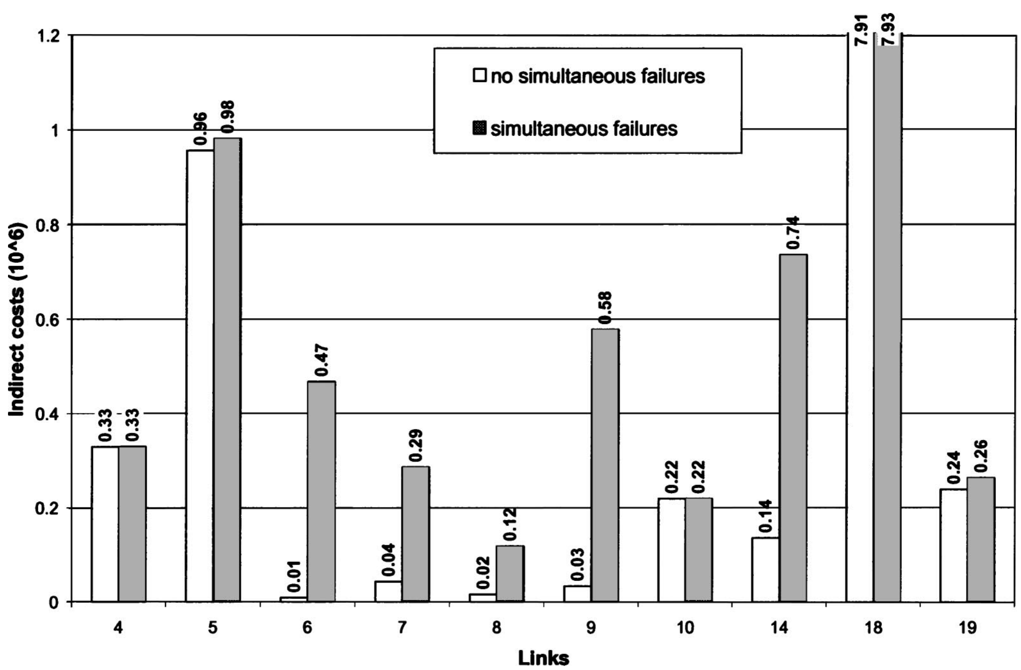

Fig. 8. Reduction in total additional indirect cost with a single intervention

mon cause failure and network connectivity suggest that intervention should be made on a different link (14) than if the failures were treated as not due to a common cause and detours were always possible (4).

Conclusions

Two examples were used to show that indirect costs for an infrastructure network with common cause bridge failure cannot be estimated assuming that the probability of simultaneous failure is negligible. The first example, on a simple network, showed the indirect cost estimate for all of the network condition states. The second example, on a complex network, showed the difference in the possible reduction of additional indirect costs and the intervention sequence with a single intervention if the probability of simultaneous bridge failure is assumed alternately as negligible and not negligible. The main conclusions are that, if bridge failure is due to a common cause, the assumption that the probability of simultaneous bridge failure is negligible in that it

- Alters estimation of the total additional indirect costs;
- Overestimates the expected additional indirect costs associated with NCSs with only one failure;
- Results in only a slight difference in the estimated possible reduction of additional indirect costs with a single intervention if there is no change in the method of indirect cost incurred;
- Can result in large differences in the estimated possible reduction of additional indirect costs with a single intervention if there is a change in the method of indirect cost incurrened; and
- Can alter the optimal intervention sequence.

Next generation BMSs, that take into consideration multiple hazard scenarios such as floods, earthquakes and traffic load, must consider the impact of common cause failure on indirect costs in order to determine the optimal allocation of resources. Further work is required, however, to identify the severity of the observed differences using probabilities of failure that are representative of in-service structures.

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Notation

The following symbols are used in this paper:

A_F = failure of bridge A;
A_S = survival of bridge A;
C = indirect cost in an infrastructure network;
C_E = indirect cost associated with the loss of economic activity;
$C_{\mathrm{NCS}i}$ = indirect cost in network condition state i;
$C_{\mathrm{NCS}0}$ = indirect cost in fully operational network condition state;
C_T = indirect cost associated with prolongation of travel;
CV = cost per vehicle/day if travel is not possible;
CVK = cost per vehicle kilometer of travel;
d_d = length of detour d;
d_{ij} = distance between nodes i and j;
d_l = length of link l;
IC_a = indirect cost when bridge A and only bridge A has failed;
n = total number of network condition states;
S = sample space;
v_{ij} = vehicles on the link between nodes i and j;
α = fraction of incoming flows, v_{wa} and v_{wc}, on simple network that bifurcate; and
ν_l = number of vehicles on link l.

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