Evaluation of Intervention Strategies for a Road Link in the Netherlands

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Abstract

In the management of road infrastructure, of which road links are a part, it is important to determine and follow optimal intervention strategies, i.e. ones that yield the minimum negative impacts on all stakeholders. In practice, however, this is often not done, because the consideration of the impacts to all stakeholders, both during and between the executions of interventions, requires both 1) an orthogonal and quantifiable impact hierarchy, and 2) an optimization model that allows the consideration of the levels of service provided by multiple objects and how they change over time. In order to determine the optimal intervention strategies to be followed, the authors developed such an impact hierarchy to allow consideration of impacts incurred by multiple stakeholders and developed a deterministic optimization model using mixed-integer nonlinear programming. In this paper the impact hierarchy and the model are used to determine the optimal intervention strategy for a road link in the Netherlands. The strengths and weaknesses of the proposed impact hierarchy and the optimisation model are discussed, along with the sensitivity analysis to validate the stability of the optimal intervention strategy upon the variations of the impacts.

Keywords: Total cost analysis; Multi-stakeholder approach; Road asset management; Optimization; Mixed-integer nonlinear programing.

1 Introduction

In the management of public road infrastructure it is important to determine intervention strategies[1] (ISs) that minimize the total of all negative impacts on all stakeholders within an investigated time period. In order to determine such optimal intervention strategies (OISs) it is necessary to take into consideration the different types of stakeholders (e.g. owner and users) and the different types of impacts (e.g. intervention cost, loss in travel time, vehicle operation cost, CO_2 emission, etc) that they incur, both during the execution of interventions and between the execution of interventions. This requires the development of an impact hierarchy, which is complete, orthogonal and quantifiable (OECD, 2001; Kumares and Samuel, 2007; B Adey et al., 2012).

Once impacts are classified, how they change over time when each ISs is followed needs to be predicted and the OIS, among them determined. The models used in infrastructure management to determine OISs are, in general, either deterministic or probabilistic. Deterministic models are used, for example, in the pavement management system HDM-4[2] and in research (Ferreira et al., 2002a; Ouyang and Madanat, 2004a, 2006a) to model the evolution of the condition of bridge elments due to both deterioration and improvement probabilistically as transistions between discrete condition states.

In this paper, an example is presented in which the impact hierarchy proposed by (B Adey et al., 2012), and a deterministic mixed-integer nonlinear programing (MINLP) model proposed in (N Lethanh and B Adey, 2012) are used to determine the OISs for a road link composed of an urban asphalt highway road section and a number of reinforced concrete (RC) overpasses in the Netherlands. The impact hierarchy of (B Adey et al., 2012) was developed by the authors as no complete hierarchy could be found in literature that could satisfactorily be used in the determination of OISs for public roads. The deterministic MINLP model was used to avoid the problem of dimensionality when dealing with multiple objects that maybe in multiple condition states in multiple time periods. It is shown that such an approach can be used to determine OISs for road links comprised of multiple objects and taking into consideration the impacts on multiple stakeholders simultaneously; something that if implemented consistently would significantly reduce the negative impacts related to road infrastructure.

2 Impact hierarchy

In the impact hierarchy developed by (B Adey et al., 2012) for public road agencies, a stakeholder is defined as an individual, group, or organization, which is affected by changes to public roads. Being a stakeholder is time dependent. For example, when a person is driving a vehicle on a road the person is a user at that point in time, and when the person is off of the road and in his/her house far from the road, the person is part of the indirectly affected public. It is considered that all stakeholders can be grouped as either first level or second level stakeholders.

[1] Intervention strategies consist of the activities that should be executed on infrastructure taking to consideration the condition of the infrastructure and how these activities are to be executed.
[2] HDM-4 is a widely used deterministic pavement management system developed by the World Bank group

The first level stakeholders are those whose net negative impacts should be minimized. The second level stakeholders are those whose impacts are the outcome of the minimization of the net negative impacts of the first level stakeholders, and should be monitored.

The four first level stakeholder groups are the owner, the user, the directly affected public (DAP), and the indirectly affected public (IAP). It is assumed that all impacts to be minimized can be attributed to one of these four principle stakeholder groups. The definitions of each stakeholder group are given in Table 1. The impacts attributed to each stakeholder group are given in Table 2 and Table 3. Detailed descriptions can be found in (B Adey et al., 2012), where explanations of each impact type, how they can be broken down to a level that is quantifiable and a classification of the impact type as either economic, environmental, and societal to help to ensure orthogonality are given.

Table 1: Stakeholder groups (adopted from Adey2012)

Stakeholder group	Definition	Examples
Owner	The persons who are responsible for decisions with respect to physically modifying the infrastructure	A federal road authority
Users	The persons who are using the roads	A driver and passengers of a vehicle on a road.
Directly affected public (DAP)	The persons who are in the vicinity of the road but are not using it	Persons in a house next to the road that hear vehicles driving on the road.
Indirectly affected public (IAP)	The persons who are not in the vicinity of the road but are affected by its use	Persons in a house far away from the road that do not hear vehicles driving on the road, but are affected by a changing climate due to the emissions produced by vehicles driving on the road.

As can be seen from Table 2 and Table 3, under each stakeholder group, the impact types are defined at different levels (hereafter referred as impact level). The impact types can be subdivided at increasingly fine levels until the impact of each type can be reasonably and objectively quantified and modeled. In the tables, 2 levels of impact types are shown but more can be further defined if required. The first level consists of composite impact types such as level of service, safety, or operation efficiency, which are considered as overall representations of important aspects. The second level of impact types is defined in greater detail compared to that of the first level. The impact type at this level can be directly quantified if there is no further requirement to acquire their value and measuring units. If there is need, impact types in level 2 then becomes a secondary composite types, whose values are computed by aggregating the values of impact types in the third level of impact types.

Table 2: Impact hierarchy to two levels for the owner and user

Stake-holders	Level 1	Level 2	Description
Owner	Level of service (intervention)	Labor	the economic impact of people performing tasks
		Material	the economic impact of people ensuring that materials are available for use
		Equipment	the economic impact of people ensuring that equipment is available for use
User	Safety (accident)	Property damage	the economic impact of repairing the vehicle
		Injury	the societal impact due to the injury
		Death	the societal impact due to death
	Operation efficiency (travel time and vehicle operation)	Work	the economic impact of wasting work time travelling
		Leisure	the economic impact of wasting leisure time travelling
		Operation	the economic impact of people ensuring that fuel and oil is available for use
		Maintenance	the economic impact of people repairing vehicles and ensuring that materials, e.g. tires and brake pads, are available for use
	Operation quality (comfort)	Physical	the societal impact of obtaining for example, bruises from an extremely bumpy ride
		Psychological	the societal impact of having for example, anxiety due to a perceived increase in the probability of being involved in an accident, or of seeing things while travelling.
	Environment preservation (noise)	NA	the societal impact due to the user coming in contract with sound emissions

Table 3: Impact hierarchy to two levels for the directly affect public and the indirectly affected public

Stake-holders	Level 1	Level 2	Description
Directly affected public (DAP)	Safety (accident)	Property damage	the economic impact of repairing property damaged due to a vehicle coming off of the road
		Injury	the societal impact due to the injury
		Death	the societal impact due to death
	Operation quality (conform)	Physical	the societal impact of physical changes due to people travelling on the road, e.g. due to vibrations
		Psychological	the societal impact of having for example, anxiety due to a perceived increase in the probability of being involved in an accident, due to others travelling.
	Environment preservation (noise)	NA	the societal impact due to the directly affected public coming in contract with sound emissions
Indirectly affected public (IAP)	Safety (accident)	Injury	the economic impact due to an injury
		Death	the economic impact due to a death
	Socio-economic activity	Persons	the impact of not on persons of not being able to transport people
		Goods	the impact of not being able to move goods
		Employment	the impact of interventions in terms of employing people
	Environment preservation (particle emission)	CO_2	the impact due to the emissions
		PM10	the impact due to the emissions
		Nitrogen	the impact due to the emissions
		CO	the impact due to the emissions
		Aldehydes	the impact due to the emissions
		Nitrogen dioxide	the impact due to the emissions
		Sulphur dioxide	the impact due to the emissions
		Polycyclic aromatic	the impact due to the emissions
		Hydro carbons	the impact due to the emissions
		Dust	the impact due to the emissions

3 Model

3.1 General

The methodology proposed in (N Lethanh and B Adey, 2012) consists of two main steps:

- Step 1: determine the optimal intervention return periods for each object, or group of objects, in the road link for each intervention type, (e.g. if the intervention to be executed is to resurface the pavement, than the optimal intervention is when the pavement roughness value is 80 mm/m) as well as the times of intervention for each object, or group of objects, taking into consideration the condition states (CSs) of each at the beginning of the investigated time period. The distinction between objects and groups of objects is made because in order to analyze all possible ISs for a road link it is necessary to consider ISs where interventions are executed on objects individually, e.g. at the time of the execution of an intervention on object A, no other intervention is being executed on the link, and ISs where interventions are executed on multiple objects simultaneously, e.g. at the time of the execution of an intervention on object A another intervention is being executed on object B in the link. The latter of which requires the definition of the combination of CSs that trigger the intervention and the assessment of the impacts incurred during the execution of the multiple interventions simultaneously, something that is not simply the addition of the impacts incurred during the execution of intervention on each object individually

- Step 2: determine the intervention times for each object, or group of objects, taking into consideration impact constraints, something that can be done using priority rules

The reader is referred to (N Lethanh and B Adey, 2012) for a full description of the model and the steps to implement the model. A short description is provided here for the reader's convenience.

3.2 Optimal intervention return periods (OIR) for each object or group of objects

The objective function of the MINLP model to be used to determine the OIR periods within an investigated time period T, is shown in Eq. **(1)**.

$$Min\Psi = \sum_{l=1}^{L}\sum_{n_l=1}^{N_l}\left[\int_0^T \sum_{x=1}^{X} f_{n_l}^{k_{n_l}}(t,x)\cdot e^{-\rho\cdot t}dt + e^{-\rho\cdot t}\sum_{x=1}^{X} g_{n_l}^{k_{n_l}}(d,x)\right] \quad (1)$$

where,

Ψ	is the total impact;
l	is the index of the link ($l \in (1,\cdots,L)$). L is total number of links;
n_l	is the index of object in link l ($n_l \in (1,\cdots,N_l)$). N_l is total objects of link l;
T	is total of investigated time period (years);
x	is the index of impact indicator (e.g. labors, materials, gasoline, CO_2, etc). X is total numbers of impact indicators considered in the impact hierarchy (B Adey et al., 2012);
k_{n_l}	is index of intervention type pre-selected for object n in the link l;
ρ	represents the discount factor;
d	represents the duration of intervention;
$f_{n_l}^{k_{n_l}}(t,x)$	represents the values of impacts associated with impact indicator x between the execution of IS k on object n of the link l. It is expressed as a function of time t;
$g_{n_l}^{k_{n_l}}(d,x)$	represents the values of impacts associated with impact indicator x during the exectution of IS k on object n of the link l;

The objective function in Eq. (**1**) is a general formulation of the deterministic model, which can be solved by mixed integer nonlinear programing (MINLP) optimization. The full form of Eq. (**1**) includes both binary and non-negative variables that are required to solve the equation. The optimization program was written in AMPL language and the optimization procedure can be implemented by using the MINLP solvers (Bonami and Lee, 2007; Bussieck et al., 2010).

In Eq. (**1**), the function *f(t,x)* and *g(d,x)* can be of any form supported by the data produced from empirical studies. One of the most common functional forms used in practice is the exponential function, which has been used, for example, to model the evolution of vehicle operation costs (VOC) (OCL, 1999; Ouyang and Madanat, 2006a), and accident rate (Kumares and Samuel, 2007). The solution to Eq. (**1**), for a specific type of intervention, is equivalent to the solution obtained from determining the OIR for interventions of that type, which can be done using the MINLP models given in (N Lethanh and B Adey, 2012). A brief of the derivation of the MINLP model is given in the Appendix.

The OIR for each object is determined by comparing the average negative impact that results from each possible ISs and selecting the one that results in the smallest negative impact. The average annual impact Θ is calculated according to following equation.

$$\Theta_{n_l}^{k_{n_l}} = \frac{\Psi_{n_l}^{k_{n_l}}}{T_{n_l}^{k_{n_l}}} \tag{2}$$

where $T_{n_l}^{k_{n_l}}$ is return period when intervention type k_{n_l} is executed on object *n* of link *l*. The return period is estimated by using Eq. (**3**). The OIS is then determined as follow:

$$k_{n_l}^{*} = \arg\underset{k_{n_l}\in K_{n_l}}{MIN}(\Theta_{n_l}^{k_{n_l}}) \tag{3}$$

Once the OIR for each object, or group of objects, is determined, their condition states at the beginning of the investigated time period can be taken into consideration and the exact times of intervention in *T* can be determined. For example, a concrete bridge has OIR of 15 years and at present it has been in service for 9 years, then the elapsed time to the next intervention is 6 years.

3.3 Intervention times with impact constraints

It is not always possible to execute all of the interventions that are theoretically optimal due to constraints on impacts, e.g. the amount of impacts incurred by the owner through the execution of interventions, i.e. intervention costs. Such constraints are introduced in the model on a yearly basis as:

$$\sum_{n=1}^{N} g_n^k(d,x) \le B^k(t,x) \tag{4}$$

where $B(t)$ is the allowable limit per impact type k in year t.

The introduction of impact constraints also makes it necessary to deal with the situation when allowable limits are reached, i.e. a decision has to be made as to which theoretically optimal interventions will not be executed and if they are not executed a decision has to be made as to when they will be executed, and with the situation when allowable limits are not reached, i.e. a decision has to be made as to what will be done with the portion of the allowable impacts that are not used, e.g. the excess money. These two situations are dealt with using priority rules, as done in (NCHRP, 1992; Morcous and Lounis, 2005; Nam Lethanh and Bryan Adey, 2013) as follows:

If the sum of all impacts of one impact type:

- is greater than the allowable limit of at least one impact type, i.e. not all objects that should have an intervention can, the object on which an intervention would have the highest reduction in total impacts within the selected year is selected for intervention, if the execution of the intervention does not result in an exceedance of the allowable limits for an impact type, otherwise the object is rejected within the selected year (and becomes a candidate for intervention within the next year) and the object with the next highest reduction in total impacts within the selected year is selected, and so on.

- is less than or equal to the allowable limits of all specific impact types, then all possible interventions are executed. The difference between the allowable limit and the sum of the specific impacts are added to the allowable limit in the following year, when applicable, e.g. budget, otherwise they are not, e.g. noise, accidents;

This procedure is repeated at each year during the investigated time period.

4 Case study

4.1 Infrastructure

The case study is the determination of the OIS for an 7.9 km section of the A20 highway from the intersection Kleinpolderplein to the intersection Terbregseplein, in the ring of Rotterdam, the Netherlands (Fig. 1-a). The link is located in a densely populated area and was considered to consist of 8 objects; 7 RC bridges and one 5.72 km long asphalt road section, i.e. the pavement over the entire road link is seen as a single object. It has 6 traffic lanes (4 main lanes and 2 narrow emergency lanes). Between July 30 and August 14, 2011, the 5 cm top layer of asphalt was renewed for all 6 lanes on the road section, including the asphalt on the bridge decks, and the construction joints of all 8 bridges were replaced (Fig. 1-a). General information of the objects is summarized in Table 4. and (Fig. 2).

<Insert Figure 1 Here>

<Insert Figure 2 Here>

Table 4: Objects

Description	Objects							
	Bridge 1	Bridge 2	Bridge 3	Bridge 4	Bridge 5	Bridge 6	Bridge 7	Road section
Width (m)	15	30	15	30	30	30	30	60
Length (m)	210	330	240	550	190	310	350	5’720

4.2 Intervention strategy types

The investigated intervention strategy types (ISTs) (**Table 5**) were comprised of three different groupings of objects on which interventions were to be simultaneously executed (IG) and four traffic configurations (TC) implemented during the execution of the interventions.

Table 5: Investigated intervention strategy types (IST)

Traffic configuration			Intervention bundle		
			IG-1	IG-2	IG-3
Abb.	Name	Description	Interventions on all objects executed independently	Interventions on all bridges executed simultaneously. Interventions on pavement are executed independently from bridges	Interventions on all objects executed simultaneously
TC-1	4-0	in the weekends, both directions (a and b) of traffic are closed. In the weekdays, both directions are opened in 4 narrow lanes	IST-1	IST-5	IST-9
TC-2	Closed on weekends	In the weekends, 1 direction is closed and 1 direction is opened. In the weekdays, both directions are opened	IST-2	IST-6	IST-10
TC-3	Closed for multiple days	In the weekends, 1 direction closed and 1 direction open. In the weekdays, 1 direction is closed and 1 direction is opened	IST-3	IST-7	IST-11
TC-4	Combination of closed for multiple days and on weekends	In weekends, direction a is closed and direction b is opened. Also, if direction b is closed, then direction a is opened. In the weekdays, direction a is closed and direction b is opened.	IST-4	IST-8	IST-12

4.3 Traffic simulation

In order to evaluate the impacts during the execution of the interventions traffic flow over the network was modelled. This was done using a static traffic assignment (STA) model. The STA model was analysed using an extracted graph (Fig. 3) containing the most relevant changes in traffic patterns caused by each TC (Cascetta, 2001). The graph in Fig. 3 represents an ordered sequence of road sections (links or arcs) and road intersections (nodes). Origins and destinations of the traffic demand are represented by centroid nodes within the network. These centroid nodes are assumed to concentrate the demand for traveling of a complete zone (e.g. a town nearby Rotterdam, or a city quarter). Each link contains traffic flows and at each node these flows are redistributed according to the route choice of the road users, or extra demand is generated or disappears if this node is a centroid. Interconnection with other cities external to the study area is also included in the model. In addition, trips between cities outside that study area but using parts of the modeled network are considered. (e.g. trips from Delft/The Hague to Dordrecht).

<Insert Figure 3 Here>

In the STA model, the traffic propagation from one link to the other is assumed as time-independent, i.e. in steady-state conditions. This is common in planning and design problems, or in cases where the precise emergence and distribution of congestion is not fundamental (Sheffi, 1985; Cascetta, 2001). The STA model was considered reasonable for this case study, as it was only necessary to determine macroscopic changes of flows from which extra travel related impacts due to the execution of an intervention on the entire network could be estimated.

In the STA model, the average travel time $S_a(v_a)$ for a vehicle on a road link was estimated as:

$$S_a(v_a) = t_a\left\{1 + 0.15(v_a / c_a)\right\} \quad (5)$$

where,

t_a is the total impact;

v_a is the index of the link ($l \in (1,\cdots,L)$). L is total number of links;

c_a is the index of object in link l ($n_l \in (1,\cdots,N_l)$). N_l is total objects of link l;

The first component in Eq. (5) represents the minimal travel time on road links when there is no congestion (or free-flow travel time), while the second component represents the nonlinear increase of travel time due to the queuing and speed reduction of vehicles when congestion occurs. The STA model also allows the consideration of perception distortion and heterogeneity of the road users (Sheffi, 1985; Cascetta, 2001).

The average additional travel time per vehicle for each TC for IG3, i.e. IST 1, 2, 3 and 4, are summarized in Table 6.

Table 6: Based value resulted from traffic simulation with STA model

IST	TC	Intervention duration (days)	Average DTV on road link (vehicles/day)	Average DTV deviated on other links (vehicles/day)	Average additional time per vehicle (minutes)
9	1	16 days (3 weekends/2 weeks)	124'854	34'358	0.97
10	2	24 days (12 weekends)	0	159'212	1.31
11	3	14 days (2 weekends/2 weeks)	64'626	94'586	1
12	4	17 days (1 week/6 weekends)	80'058	79'154	0.81

4.4 Impact types and unit values

The impact types and the value of a unit of each are given in Table 7. The unit values are the mean values that were derived from several Dutch and European documents (e.g. (Bickel et al., 2002)). The impacts incurred to each group of stakeholders (Table 1) during interventions and in between interventions from each object are calculated based on empirical models. For example, the vehicle operation cost (VOC), which is an impact incurred by the users during the execution of an intervention and between interventions, was calculated using following equation.

$$VOC = L * 365 * DTV * V * d * c \tag{6}$$

where L is the length of the object, DTV is daily traffic volume, V is the speed of the vehicle, d is intervention time, and c is unit cost of the fuel. The empirical models used to estimate other impacts can be found in (B Adey et al., 2010; ERA-NET, 2012). The values of each unit of impact was estimated using the unit given in Table 7.

Table 7: Unit value of impact types

Stakeholders	Impact type (level 1)	Impact type (level 2)	Indicator	Unit value (€)
User	Vehicle operating cost (VOC)	VOC per light-weight vehicle	hour	1.65
		VOC per medium-weight vehicle	hour	2.67
		VOC per heavy-weight vehicle	hour	5.32
		VOC per bus	hour	5.32
	Petrol cost*		litre	0.46
	Diesel cost*		litre	0.51
	Vehicle		vehicle per year	0.86

	maintenance cost (VMC)			
	Travel time cost (TTC)	TTC during work time	hour	33.07
		TTC during leisure time	hour	9.55
	Accident	Property damage	accident	41'690
		Injury	injured person	276'568
		Fatality	fatality	2'690'108
DAP	Noise	Noise	dB per year per person	27.97
IAP	Emissions	CO_2	ton	2.4
		PM	ton	308'189
		NOx	ton	4'093
		CO	ton	3.1
		VOC	ton	1'139
		Dust	ton	30'675

Note: The prices of petrol and diesel are without tax

The impacts incurred by each stakeholder group during the execution of each intervention, i.e. for each grouping of interventions and each traffic configuration are given in Table 8.

Table 8: Impact per object during intervention (unit=1'000 €)

Traffic configuration	Stake holders	Intervention grouping										
		IG-1								IG-2		IG-3
		Bridge 1	Bridge 2	Bridge 3	Bridge 4	Bridge 5	Bridge 6	Bridge 7	Road section	Bridge 1 -Bridge 7	Road Section	Bridge 1-Bridge 7+Road Section
TC-1	Owner	406	676	424	919	522	654	698	2'829	2'810	2'829	5'390
	User	47	68	52	95	44	58	71	1'995	437	1'995	2'432
	DAP	8	8	8	8	8	8	8	16	57	16	73
	IAP	5	6	5	9	5	6	6	137	42	137	179
	Total	466	759	490	1'031	578	727	784	4'977	3'345	4'977	8'074
TC-2	Owner	288	558	306	800	404	536	580	2'761	2'691	2'761	4'762
	User	124	124	124	124	124	124	124	1'243	870	1'243	2'114
	DAP	20	20	20	20	20	20	20	20	142	20	163
	IAP	33	36	34	43	32	36	37	436	251	436	687
	Total	465	739	484	988	581	716	762	4'460	3'955	4'460	7'725
TC-3	Owner	268	538	286	780	384	516	560	2'661	2'672	2'661	5'221
	User	49	60	52	80	47	58	62	1'645	408	1'645	2'053
	DAP	8	8	8	8	8	8	8	16	57	16	73
	IAP	9	10	9	13	9	10	10	262	70	262	332
	Total	334	616	355	882	447	592	640	4'584	3'207	4'584	7'679
TC-4	Owner	258	528	276	770	374	506	550	2'701	2'312	2'701	4'912
	User	45	69	60	90	56	67	71	1'996	459	1'996	2'455
	DAP	8	8	8	8	8	8	8	16	57	16	73
	IAP	8	9	8	12	8	9	9	241	63	241	304
	Total	319	614	352	881	445	590	639	4'954	2'890	4'954	7'744

As can be seen, the impacts incurred by each stakeholder group during the execution of each intervention vary significantly. For example, when an intervention is executed on the road section alone, which occurs if IG-1 and TC-1 are used, the owner impact is 2'829x10^3€. However, when an intervention is executed on the road section alone, and TC-2 is used, the impact is 2'761x10^3€, which is about 2.4 % lower than if TC-1 is used. It is interesting to note that during the execution of interventions on bridges, the impacts incurred by the owner are considerably greater than they are on other stakeholders (on average, 80% vs. 10%). This is partially due to the fact that because the intervention costs (labor, materials, equipment) on bridges are relatively high was considerably high (e.g. an intervention on bridge 1 costs the owner 406'201 €) with respect the amount of time that it takes to execute an intervention and during which the user is adversely affected. (e.g. an intervention on bridge 1 takes 8 days and the impacts incurred by the user and public during this time are 10'733 € and 2'308 €

During the execution of an intervention on the road section, the impacts incurred by the owner and users are not significantly different (on average 55% vs. 40 %). This is partially because the relatively extra work travel time incurred (0.7 minute/user/day, making up $1.5x10^6$ € extra) off set the owner cost of intervention (e.g. an intervention on the road section costs $2.83x10^6$ €).

During the execution of an intervention on both the road section and bridges, the impacts incurred by the DAP and IAP are significantly smaller than those incurred by owner and users (1% to 5%). This is partially due to the fact that there is a relatively small number of people (1'500) considered to be adversely affected by the execution of inteventions and partially due to the fact that the interventions would not generate much more noise than normal use of the road. The impacts incurred by the execution of interventions on the road section and on each of the bridges are roughly the same per day (1'015 €/day and 2’500 €/day/km for DAP and IAP, respectively).

The proportions of impacts incurred by IAP when an intervention was executed on the road section were higher than the total amount due to the execution of interventions on all bridges (136,906 € vs 41'805 €). This is principally due to the fact that the impacts incurred by the IAP, e.g. emissions, are considered to be directly related to additional time vehicles travel and the speed at which they are travelling, during the execution of an intervention.

The impacts incurred by stakeholders between interventions are assumed to change over time due to the deterioration of the road condition. This change was modelled using exponential functions (see the Appendix). The use of exponential functions have been used by past researches (OCL, 1999; Ouyang and Madanat, 2004b, 2006b; Kumares and Samuel, 2007) and in the abscence of more detailed information was consdiered to be a reasonable choice. The evolution of the impacts on the eight objects over 30 years if no interventions are executed are shown in Fig. 4. The figure shows the evolutions of impacts incurred by four main stakeholders (Owner, Users, DAP, and IAP), values at any point on the curves represent the cummulative values of impacts under the four main stakeholders. Impact values of owner are considered as routine maintenance cost.

As can be seen in the figure, for both the road section and the bridges, impacts incurred by the users are the largest (approximately 73% due to the use of the road section and 47% due to the use of the bridges). The second largest impacts are incurred by the DAP (approximately 16% due to the use of the road section and 36% due to use of the bridges). The impacts incurred by the IAP are approximately 4% due to the use of the road section and 10% due to use of the bridges . The impacts incurred by the owner, due to routine maintenance on both the road section and the bridges are approximately 7% .

<Insert Figure 4 Here>

4.5 Results

The total absolute average annual impacts (estimated by using Eq. (2) that are incurred when each OIS of each IST are followed, as well as the relative average annual impacts when each OIS of each IST is compared with the reference IS (the OIS of IST1) are given in Table 9. The OIS, of all OISs, that results in the lowest overal impact is of IST-9 (56 x 10^3 € less than the reference

IS).

Table 9: Average annual impacts of IST

IST	Intervention time on objects (years)								Absolute average annual impact (€)	Relative average annual impact (€)
	Bridge 1	Bridge 2	Bridge 3	Bridge 4	Bridge 5	Bridge 6	Bridge 7	Road section		
1	28	31	28	30	33	32	31	10	584'271	0
2	28	31	27	29	34	31	31	8	672'854	88'583
3	22	28	21	27	29	28	28	8	644'259	59'988
4	21	28	21	27	29	28	26	10	585'667	1'396
5	24	24	24	24	24	24	24	10	582'492	-1'779
6	27	27	27	27	27	27	27	8	671'120	86'849
7	23	23	23	23	23	23	23	9	616'546	32'275
8	26	26	26	26	26	26	26	10	584'993	722
9	14	14	14	14	14	14	14	14	527'921	-56'350
10	13	13	13	13	13	13	13	13	544'630	-39'641
11	13	13	13	13	13	13	13	13	547'212	-37'059
12	13	13	13	13	13	13	13	13	545'924	-38'347

As can be seen from Table 9, the OIS of IST-9 is the one with the lowest average annual impact on stakeholders (a reduction of 56'350 € with respect to the reference IS). It can be also seen that the OISs that include grouped interventions, i.e. ISs of IST-9, IST-10, IST-11, and IST-12, result in lower average annual negative impacts than that the OISs where interventions are not grouped, e.g. absolute average annual impacts when the OIS of IST9 is followed are 527'912 € which is about 9% lower than the absolute average annual impacts when the OIS of IST1 is followed 584'271 € . This is, in general, because by grouping interventions there are significant reductions to the owner impacts of execution the interventions, e.g. only one work site as to be made, as opposed to multiple work sites, (e.g. the total impacts incurred by the owner during the execution of interventions on road section in IST-5 (TC-1 and IG-2) were estimated as 5'639x10^3 under IST-9 (TC-1 and IG-3). Such reductions occur, for example, due the reduction in effort in setting up traffic barriers to establish and maintain the traffic configuration, e.g.. The impacts incurred by the owner of setting up traffic barriers during the execution of the interventions in the ISs of IST-5 were estimated to be 278. x10^3 and 35.55x10^3 for the road section and each bridge, respectively, making the total impact related to setting up traffic barriers 527 x10^3(=(278.5+7*35.55)x10^3). It is noted that the impacts incurred by the owner due to the setting up of traffic barriers were calculated based on the assumption that the execution of interventions on each object is carried out separately and not grouping the objects in one package. These impacts during the execution of the interventions in the ISs of IST-9 were estimated to be 278.50 x10^3 € for the interventions to be executed simultaneously on the road section and the bridges in each intervention return period; a reduction of nearly 50% over those estimatedfor the interventions in the ISs of IST-5, in which interventions are executed on all bridges simulateneously and the road section seperately.

It can also be seen that the absolute, and relative, average annual impacts of the OISs of IST-9, IST-10, IST-11, and IST-12 are not significantly different (e.g. in comparison with the OIS of IST-9, the variations of impacts of the other OISs of each IST are only about 1%). These small differences are mainly due to the differences in impacts incurred by the user through the extra travel time incurred by different TC (refer to Table 6). As the differences are only small, due to the redundant road network around Rotterdam there is only a slight effect on OIS, i.e. the OIR oscillates between 13 and 14 years. For example, the average annual impacts of the OIS of IST-9 were estimated to be 527'921 € and the extra travel time per vehicle was 0.97 minutes (Table 6) , while, the average annual impacts of the OIS of IST-10 were estimated to be 544'630 € and the extra time per a vehicle was 1.31 minutes

5 Sensitivity analysis

As the estimation of the unit values of the impacts, the discount rate, and the effectiveness of interventions is something that is in most cases highly subjective, a sensitivity analysis was conducted on the values of the parameters given in Table 10. These ranges were deemed sufficient to show the significance of over- and underestimation of the unit values, measured with respect to the change in the impacts related to the OIS of each IST and therefore their optimality. The effect of these variations on the optimal IST, the OISs and the average annual impacts are shown in Fig. 5 and summarized in Table 10.

Table 10: Parameters included in sensitivity analysis

Description		Parameters							
		Owner	User	VOC	Extra travel time	Discount factor	α	δ	β
Min	Percent from default value	-50%	-50%	-50%	-50%	-75%	-50%	-50%	-50%
Base value	IST7-bridge	2.67×10^6 €	1.24×10^6€	2.67€/hour	0.27 min	0.02	14'087	8'534	0.06
	IST7-road	3.47×10^6 €	0.87×10^6 €	2.67€/hour	0.70 min	0.02	40'939	23'508	0.06
	IST9	4.76×10^6 €	2.11×10^6 €	2.67€/hour	0.97 min	0.02	55'026	32'042	0.06
	IST10	5.39×10^6 €	2.43×10^6 €	2.67€/hour	1.31 min	0.02	55'026	32'042	0.06
	IST11	5.99×10^6 €	2.05×10^6 €	2.67€/hour	1 min	0.02	55'026	32'042	0.06
	IST12	5.96×10^6 €	2.45×10^6 €	2.67€/hour	0.81 min	0.02	55'026	32'042	0.06
Max	Percent from default value	+50%	+50%	+50%	+50%	+150%	+50%	+50%	+50%

Note: 2.67€/hour is base value for medium weight vehicle. For light and heavy vehicles, base values of VOC are 1.65€ and 5.32 €, respectively.

In addition, a summary of the stability of OIS and the significances in changing the OIR and the average annual impacts is also shown in Table 11.

<Insert Figure 5 Here>

Table 11: Summary of the effect of variations in selected parameters on the optimal IST, the OIS and the average annual impacts

Description	Variations in							
	Owner	User	VOC	Travel time	Discount factor	α	δ	B
Type of OIS	IST-9	IST-9	IST-9	IST-9	IST-9	IST-9	IST-9	IST-9
OIS	high	high	low	low	high	high	moderate	High
Average annual impacts	high	high	low	low	high	high	moderate	High

It can be seen that a small change in the unit values of impacts, i.e. owner, user, vehicle operating costs, travel time impacts, can result in changes in

- the OIS of each IST, e.g. the sharp increase of the OIR curves in Fig. 5 . For example, in Fig. 5-c, it can be seen that for approximately every 10% increment of change in the valuation of owner impacts there is an increase in the amount of time between interventions by 1 to 3 years.
- the optimal IST, e.g. an increase in the valuation of vehicle operating costs by +20% from the base value results in a change in the optimal IST from IST-9 to IST-10 (Fig. 5-b). In most of the cases, however, the optimal IST is stable. This can be seen by observing the optimal IST of IST-9 shown in Fig. 5, e.g. in Fig. 5-a. Changes in the value of travel time, do not result in a change of the optimal IST; it is always IST 9 (in purple).
- the average annual impacts, e.g. the sharp decrease of the impact curves in Fig. 5-a, b, and c. For example, an increase in the valuation of owner impacts by 10% from the base value results in a change in the average annual impacts of approximately $50x10^3$ € for IST-9.

Changes in the value of the discount factor ρ (Fig. 5-e)

- affect the optimal IST insignificantly, e.g. the optimal IST is still IST-9.
- greatly affect the OIS, e.g. the sharp increase in the OIR curves. If the value of the discount factor increases or decreases by a value of 0.005 from the base value (0.02), the OIR changes by approximately 4-5 years.
- greatly affect the average annual impact, the sharp decrease in the impact curves. If the value of the discount factor increases by a value of 0.005 from the base value (0.02), the change in the impact is approximately $200x10^3$ €.

This means that the smaller the value of the discount factor used the shorter the time interval between interventions becomes in the OIS and the higher the average annual impacts.

Similarly, changes in the value of parameter α (Fig. 5-f)

- affect the optimal IST, insignificantly, e.g. the optimal IST is still IST-9.
- greatly affect the OIS, For every increase/decrease of 10% from the base value, the intervention time decreases/increases between 2 to 3 years, depending on the IST.

- greatly affect the average annual impact. For every increase/decrease of 10% from the default value, the average annual impact increases between approximately 10% and 40%.

Changes in the value of parameter δ (Fig. 5-g) also affect the optimal IST, the OIS and the average annual impact, however, the effect is moderate when compared to changes in the value of parameter α.

Changes in the values of the parameter β (Fig. 5-h) also
- affect the optimal IST, insignificantly, e.g. the optimal IST is still IST-9.
- affect the OIS. Increases in the values of β by 10% from the base value result in approximately 2 year decreases in the OIR
- affect the average annual impacts. Increases in the values of β by 10% from the default value result in increases in average annual impact of 75 to 100 €.

6 Conclusion

In this paper, the optimal intervention strategy was determined for a road link in Rotterdam, the Netherlands, using the impact hierarchy developed by (B Adey et al., 2012) and the MINLP model developed by (N Lethanh and B Adey, 2012). The road link consisted of eight objects, seven reinforced concrete bridges and one 11km long road section. Three possible intervention groupings and four possible traffic configurations during the execution of the interventions were analysed.

The impact hierarchy (B Adey et al., 2012) and the MINLP model (N Lethanh and B Adey, 2012) used in the case study made it possible to determine the optimal intervention strategy for the A20 in Rotterdam. By using the hierarchy, all possible impacts incurred by all stakeholders could be quantified and double-counting was avoided. The MINLP model could be used together with the hierarchy to determine the optimal intervention strategy of each intervention strategy type and the optimal intervention strategy overall, as well as the corresponding average annual impacts..

In addition the case study showed that intervention strategies in which interventions on multiple objects were executed simultaneously, i.e. grouped, often resulted in reduced negative impacts incurred by stakeholders, especially the owners and the users, due to the elimination of effort in the execution of interventions and the elimination of disruptions to traffic flow during the execution of interventions, respectively.

Based on this work, it is believed that the combination of the impact hierarchy and MINLP model can be used to determine improved intervention strategies for road links than the ones currently being followed. Future work, however, could improve the MINLP model even further by eliminating some of the following observed weaknesses,

- It is suspected that the use of exponential functions (Appendix) could result in the overestimation of impacts once the condition becomes poor, and therefore future research should focus on the verification of the type of functions used,

- The model allows the evaluation of intervention strategies that are composed of a single type of intervention (e.g. resurfacing, reconstruction, etc). It is only possible with this model to evaluate intervention strategies that are composed of interventions of more than one type, which is something that often occurs in reality, by updating the model parameters and re-estimate the optimal intervention strategy for each new type of intervention.

- The use of priority rules in the optimization model is convenient to get the results computational fast. However, it could possibly result in non global optimal solution. This problem has been addressed in most research work on building optimization models for road networks (Ferreira et al., 2002b; Ouyang and Madanat, 2006a). Problems are, however, encountred during the implementation of these improved models due to the computational difficulty in nonlinearity and exponential growth. Future development of optimization models for management of road networks, therefore, should be focused on the development of algorithms to relax the priority rules or any heuristic assumptions in way that would ensure that global solutions are obtained

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8 Appendix

It is assumed that the impact incurred after intervention follows an increasing exponential function.

$$f(t) = \alpha + \delta \cdot exp(\beta \cdot t) \quad \text{(A. 1)}$$

where α and δ represent fixed parameters, which are assumed to be estimated empirically (e.g. the vehicle operation cost). β is also a fixed parameter that has relationship with deterioration. Values of α, δ, and β can be either positive or negative depending on the type of impact. The total impact in Eq. (1) for an individual object can be rewritten as:

$$\psi(t) = \int_0^T (\alpha + \delta \cdot e^{\beta \cdot t}) e^{-\rho \cdot t} dt + e^{-\rho \cdot t} g(d) \quad \text{(A. 2)}$$

Eq. (5) can be elaborated as:

$$\psi = \left[\frac{\alpha}{\rho}(1 - e^{-\rho T})\right] + \left[\frac{\delta}{\beta - \rho}(e^{(\beta-\rho)T} - 1)\right] + e^{-\rho . T} \cdot g(d) \quad \text{(A. 3)}$$

If an intervention is executed ν times within an investigated time period T, then the duration of intervention cycles (excluding intervention duration), is given by t/ν, and the Eq. (A.3) becomes

$$\psi = \nu \cdot \left[\frac{\alpha}{\rho}\left(1 - e^{-\rho \cdot t/\nu}\right)\right] + \nu \cdot \left[\frac{\delta}{\beta - \rho}\left(e^{\beta-\rho)t/\nu}\right)\right] + \nu \cdot e^{-\rho t/\nu} \cdot g(d) \quad \text{(A. 4)}$$

In order to find the value of variable t and ν, following constraints can be used:

$$\nu = \sum_{m=\varepsilon,1}^{M} m.\gamma_m \quad \text{(A. 5)}$$

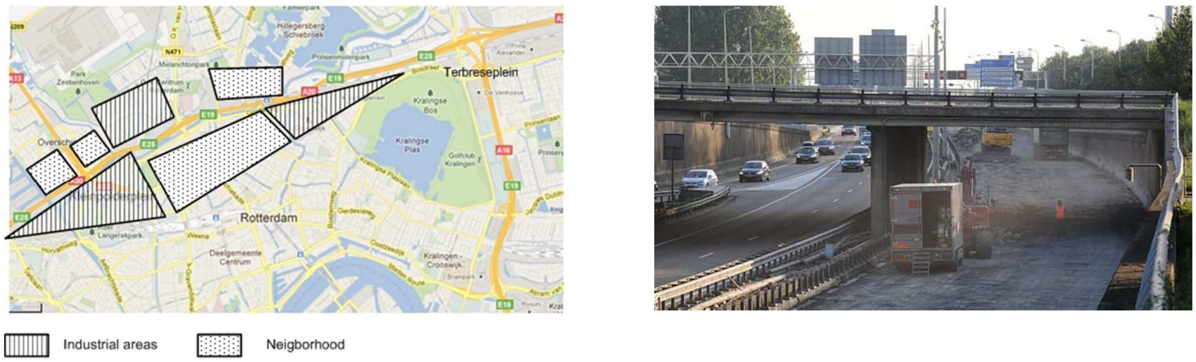
$$\sum_{m=\varepsilon,1}^{M} \gamma_m = 1 \quad \text{(A. 6)}$$

where γ is a binary variable used to enforce that ν is an integer. The value of ε is selected as a constant with a value close to zero, it is introduced so that the value of m is either ε or an integer greater or equal to 1, and to ensure that the denominator t/ν in Eq. (A.4) cannot be 0. M is a variable whose value is selected to be consistent with the upper bound on the number of intervention times ν.

Time balance constraints are introduced to ensure that the time between intervention plus the intervention time for any object cannot be more than the duration of each intervention cycle.

$$\nu.d + t \le T_{total} \quad \text{(A. 7)}$$

$$\varepsilon \le \nu \le M \quad \text{(A. 8)}$$



(a)-A20 load link (b)-Intervention

Figure 1: Intervention of A20 road link, Rotterdam

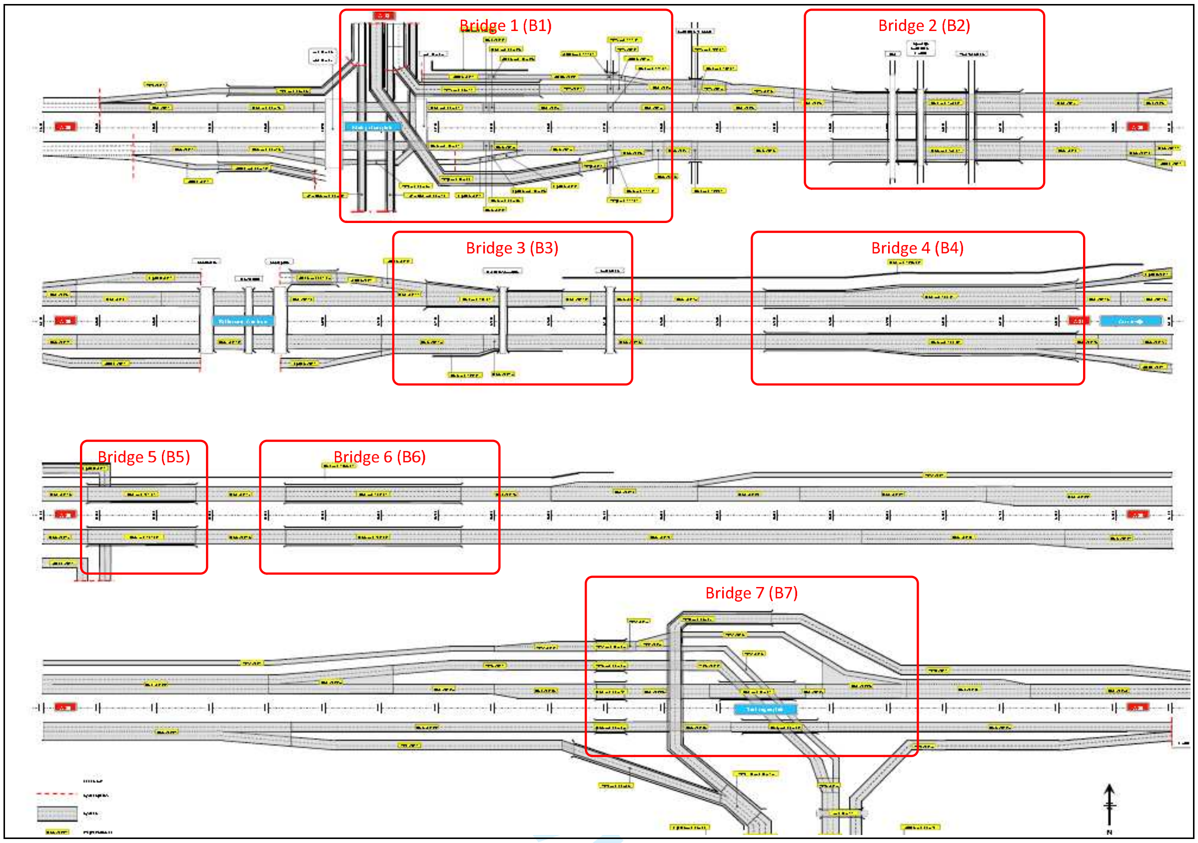
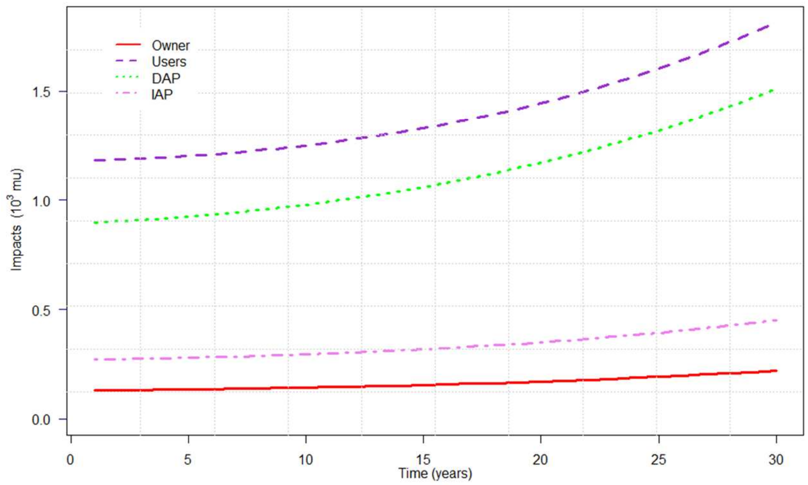
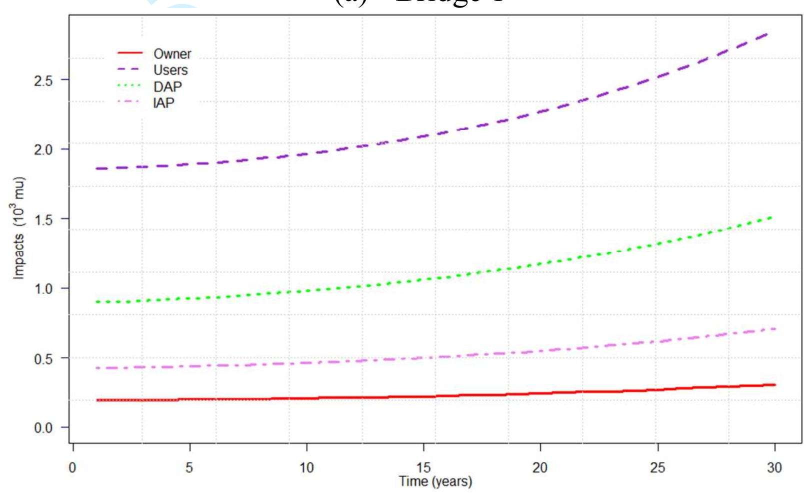


Figure 2: Locations of objects on the link

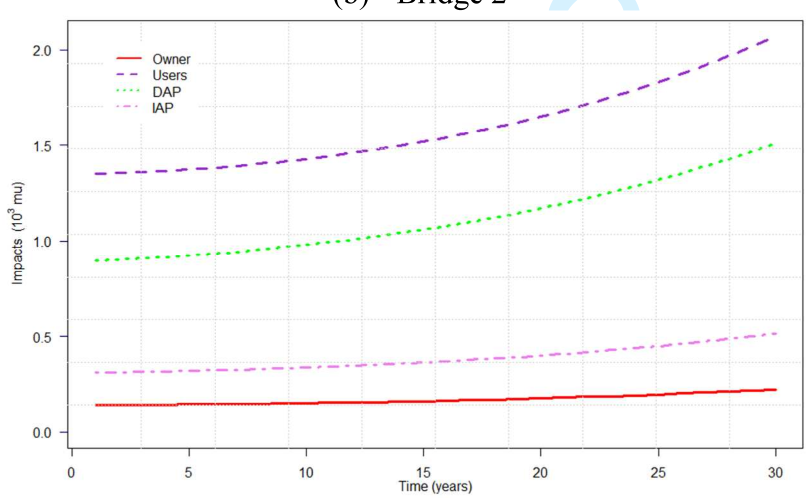
Figure 3: Representative graph for traffic simulation



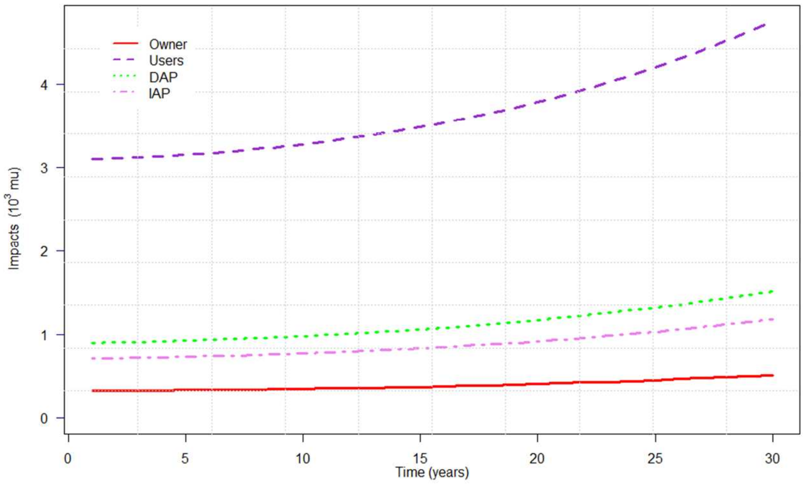
(a) - Bridge 1



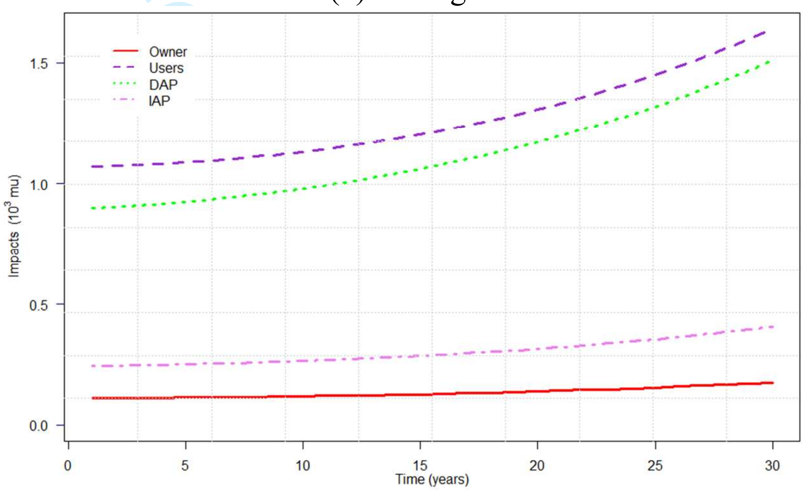
(b) - Bridge 2



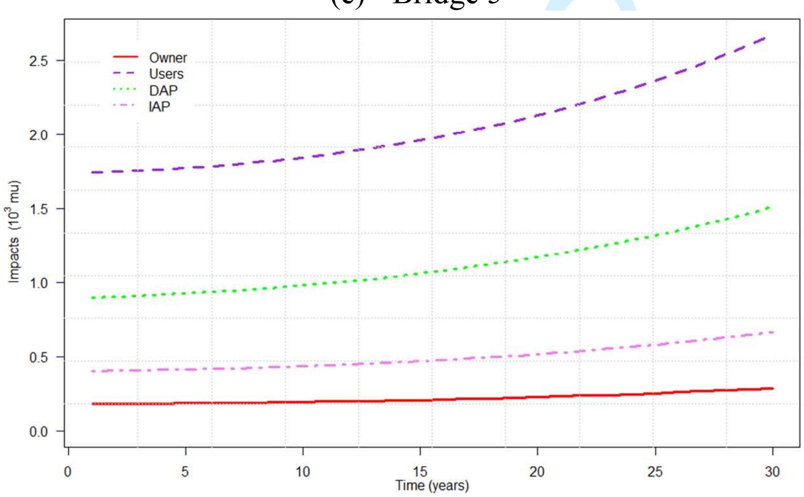
(c) - Bridge 3



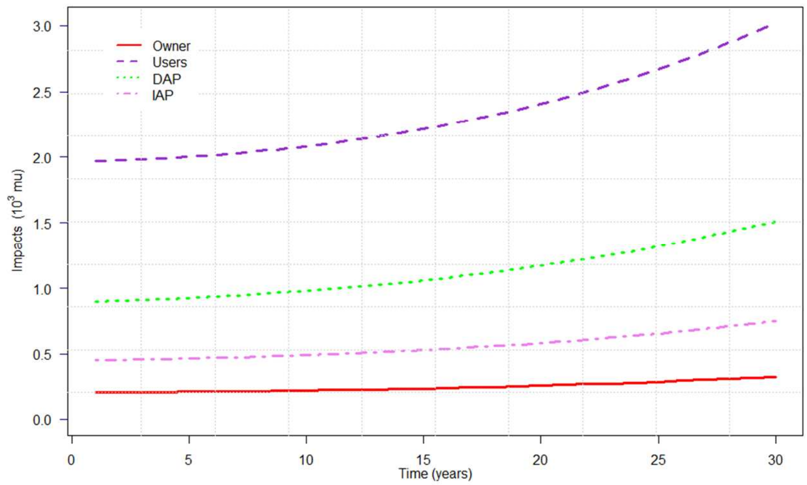
(d) - Bridge 4



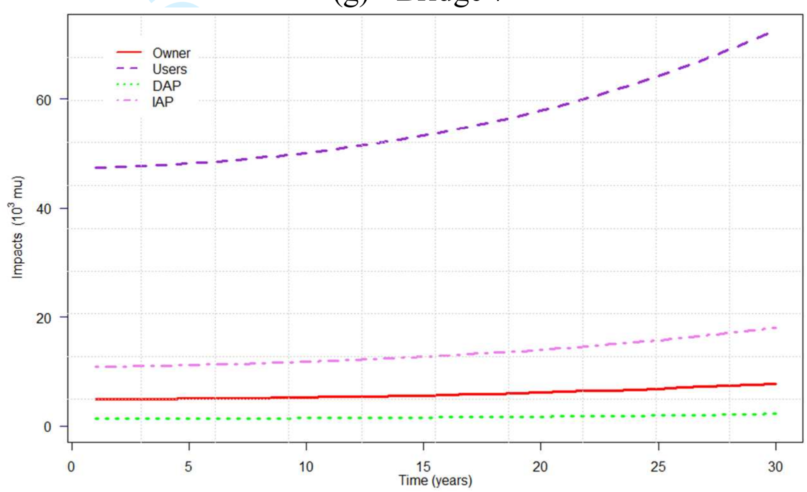
(e) - Bridge 5



(f) - Bridge 6

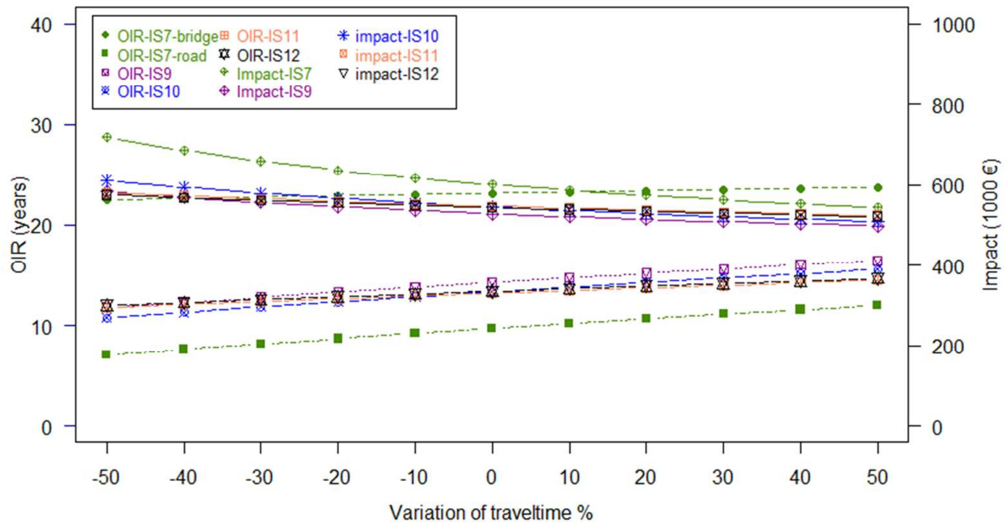


(g) - Bridge 7

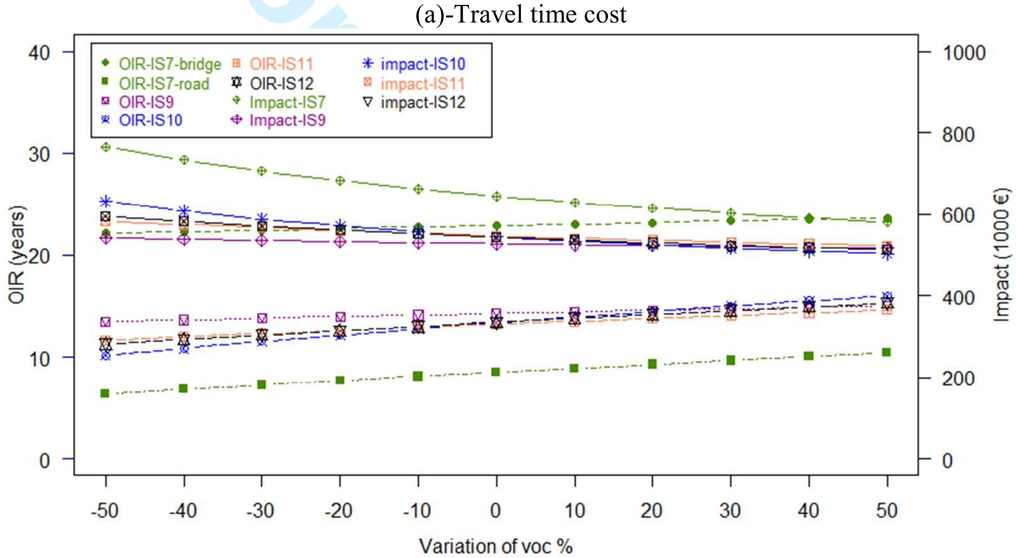


(h) – Road section

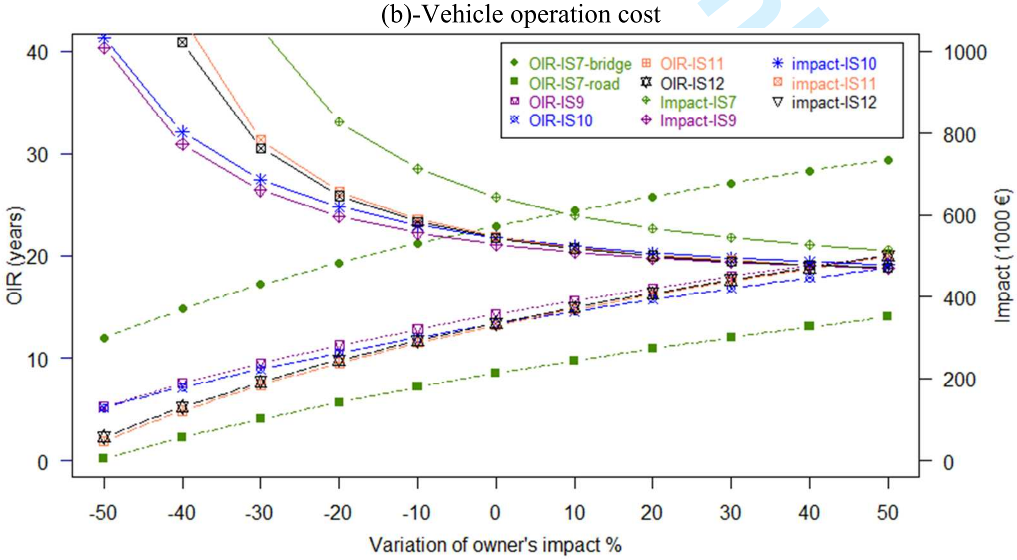
Figure 4: Evolution of impacts following the execution of interventions



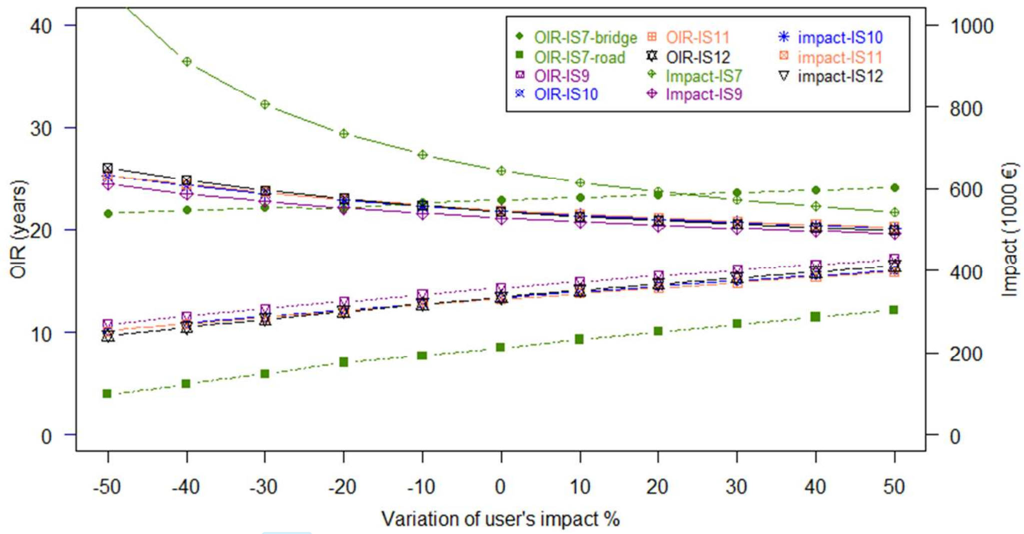
(a)-Travel time cost



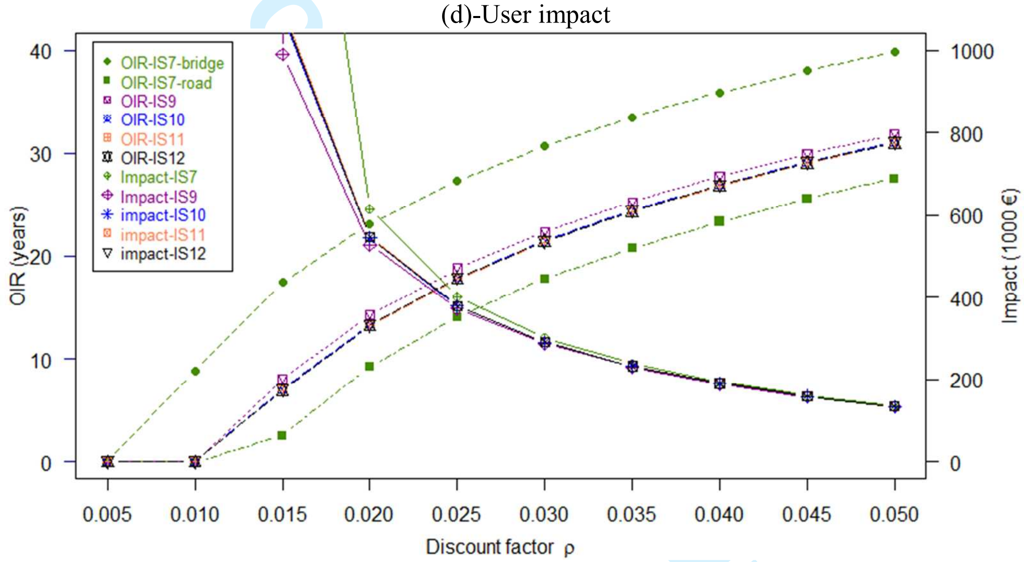
(b)-Vehicle operation cost



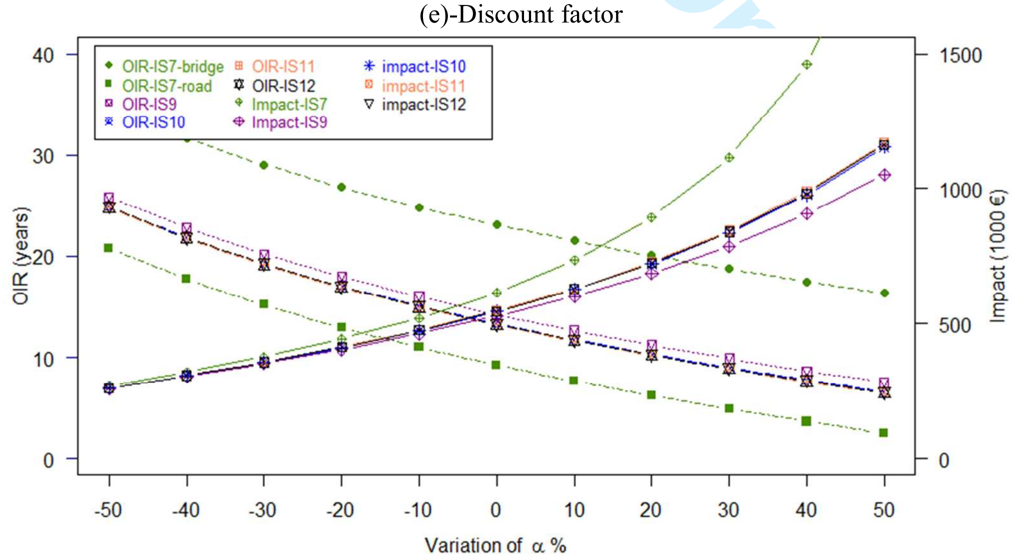
(c)-Owner impact



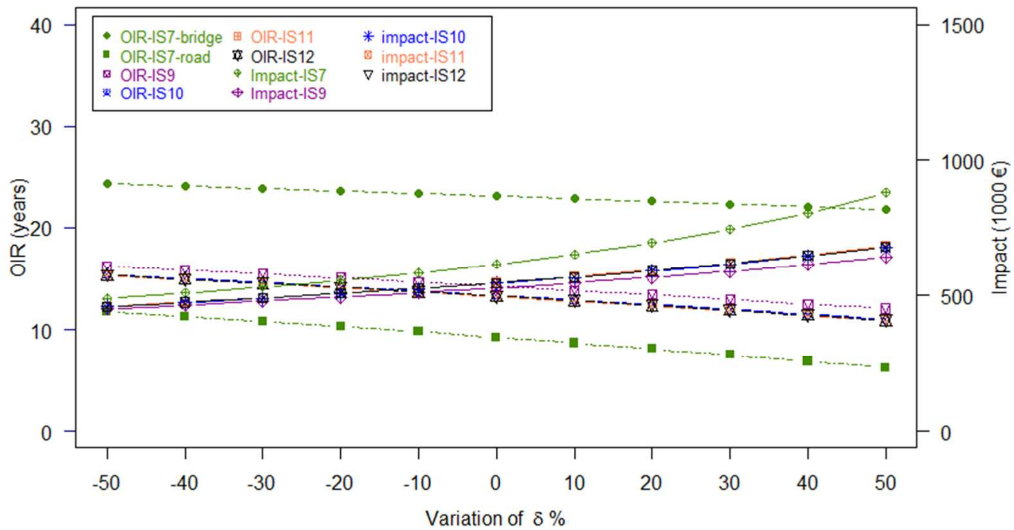
(d)-User impact



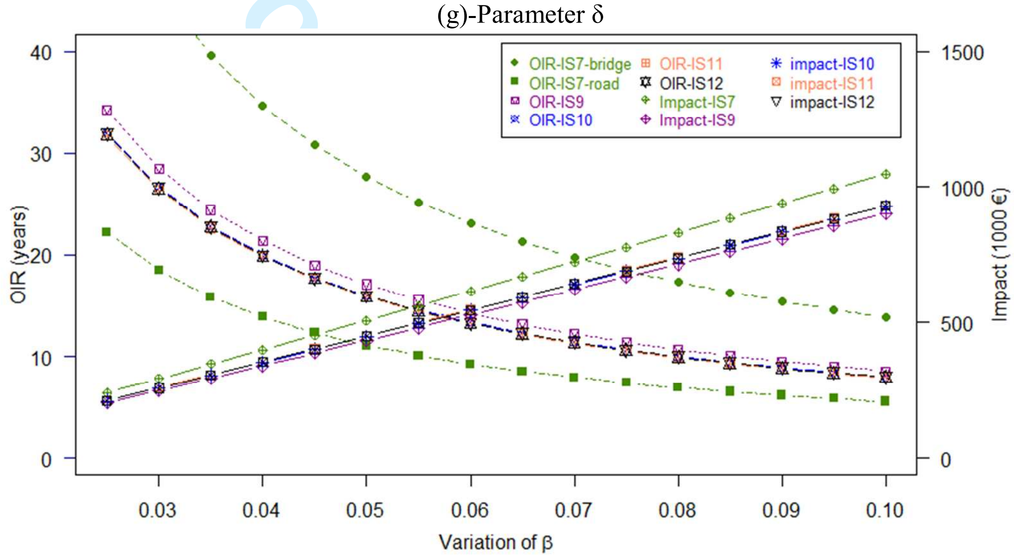
(e)-Discount factor



(f)-Parameter α



(g)-Parameter δ



(h)-Parameter β

Figure 5: Effect of variations in selected parameters on the optimal IST, the OIS and the average annual impacts