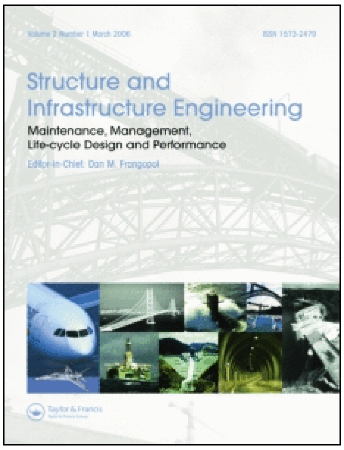

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In Switzerland, it is common practice to estimate the total benefits of new roads before they have been built and of road *improvement interventions* before they have been performed. The guidelines with respect to standardised methodologies and models to be used have been developed (VSS 2003a) and are now in use. It is not yet, however, common practice to estimate the total benefits of road *preservation interventions* and hence guidelines do not exist with respect to standardised methodologies and models to be used. In order to provide this information, the research package VSS 2004/710-716 was started. This paper presents the methodology and models proposed to be used to evaluate the total benefits of road preservation interventions in Switzerland based on the evaluation and synthesis of existing national and international literature on the relationships between pavement condition and benefits of road use conducted in project 714 of the research package. The use of the methodology and models are demonstrated by determining the optimal intervention strategy for a representative situation in Switzerland. The impact on the optimal intervention strategy of the consideration of multiple stakeholders is investigated.

Keywords: benefit analysis; cost analysis; infrastructure management; maintenance; roads and highways

1. Introduction

Road maintenance requires the planning and performing of interventions to ensure that an adequate level of service is provided. The definition of an adequate level of service is often, at least partially, defined in codes and guidelines. The interventions required in road maintenance that do not involve a change of the level of service, can be grouped into the following two categories:

- *Routine maintenance interventions*. These are interventions performed on a routine basis, i.e. at less than 5 year intervals, to prevent the unnecessary acceleration of the deterioration rate from the normally expected deterioration rate and therefore the unnecessary increase in risks related to the condition of the road section, such as accident risks. Routine maintenance interventions do not improve the overall condition of a road section or reduce the deterioration rate below the normally expected deterioration rate. They are performed between preservation interventions. Examples of routine maintenance interventions are cleaning of road side ditches, crack filling and pothole filling.
- *Preservation interventions*. These interventions are not performed on a routine basis, i.e. they are performed at regular or irregular intervals greater than 5 years, to reduce the deterioration rate of road section or to restore the condition of a road section up to, but not beyond, its original condition. They are normally performed when the condition of a road section reaches a specified threshold, e.g. a certain percentage of the surface is cracked. Examples of preservation interventions are asphalt crack sealing, chip sealing, and partial and full depth concrete repairs to restore functionality of the slab.

It is in the interest of society that roads be managed to ensure that total benefits are maximised. To achieve this goal optimal preservation intervention strategies must be followed. A preservation intervention strategy consists of the types of preservation interventions and the times when they are to be performed on an infrastructure object, in this case a road section. The subsequent changes in routine maintenance interventions are normally considered as a (positive or negative) benefit of the preservation intervention strategy. An optimal preservation intervention strategy is the one that has the largest positive difference between its net benefit and its net cost. The net benefit of an intervention strategy is the difference between its benefit and the benefit of the reference intervention

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strategy. The net cost of an intervention strategy is the difference between its cost and the cost of the reference intervention strategy. Costs, in this case, are the owner costs of performing the intervention strategy.

In order to provide the required methodologies, models and basic information to be used to systematically determine optimal preservation intervention strategies for road sections in Switzerland, the research package VSS 2004/710-716 was started. In addition to fulfilling this goal, it has provided a starting point from which future research will be conducted. The work within this research package involved exclusively the evaluation and synthesis of existing research work. It consisted of research projects that focused on the standardisation of interventions, the deterioration of pavement sections, the benefit of interventions and the additional costs of advancing or postponing interventions.

This paper presents the methodology and models proposed to be used to evaluate the total benefits of road preservation interventions in Switzerland based on the evaluation and synthesis of existing national and international literature on the relationships between pavement condition and benefits of road use conducted in project 714 of the research package. It provides the main results of the work and references the principal literature upon which the proposed methodology and models were based. A complete list of the literature investigated can be found in Herrmann *et al.* (2008). The models proposed use only variables commonly used in practice to facilitate their acceptance and use in practice. As no tests were conducted, it is expected that these models will be improved in the future when testing is conducted to further investigate the relationships between road condition and benefits. Nevertheless the systematic and logical methodology and models proposed can be used to numerically estimate all of the benefits associated with road section preservation intervention strategies and therefore to determine optimal road section preservation intervention strategies. The use of the methodology and models are demonstrated by determining the optimal intervention strategy for a representative road section in Switzerland. The impact on the optimal intervention strategy of the consideration of multiple stakeholders is investigated.

2. Benefits

A benefit of an intervention strategy is defined as a (positive or negative) consequence of the intervention strategy on a stakeholder, i.e. something that happens when an intervention strategy has been followed that would not have happened if it had not been followed. They are grouped by stakeholder, i.e. the owner, the user and the public, and benefit type, and represented with indicators (Table 1). The benefits for the owner are the reduction in routine maintenance costs. The benefits for the user are the reduction in vehicle operation costs, the reduction in accident costs, the reduction in travel time costs and the reduction in discomfort costs. The benefits for the public are the reduction in accident costs, the reduction in noise costs and the reduction in other environmental costs. Each benefit type is attributed to one stakeholder, with the exception of benefits due to the reduction in accidents. A reduction in accidents is considered to benefit both the user and the general public. The benefits are orthogonal to one another and can therefore be added (or subtracted) in the estimation of total benefits.

Total benefit is defined as the net benefit for all stakeholders over an investigated time period [0, T], i.e. the benefit for all stakeholders of one intervention strategy when compared with the benefit for all

Table 1. Stakeholders, benefit types, and benefit indicators.

Stakeholders	Benefit type	Symbol	Example benefit indicators
Owner	Reduction of routine maintenance costs (M)	$B^i_M(t)$	Man-hours needed Quantity of materials required
User	Reduction of travel time costs (TT)	$B^i_{TT}(t)$	Man-hours of work-time lost Man-hours of non-work-time lost
	Reduction of vehicle operating costs (VO)	$B^i_{VO}(t)$	Man-hours needed for maintenance Quantity of materials required, e.g. number of tyres, number of brake pads, amount of fuel
	Reduction of discomfort costs (D)	$B^i_D(t)$	Amount of physical disturbance Amount of psychological disturbance
	Reduction of accident costs (A)	$B^i_A(t)$	Amount of property damage Number and type of injuries Number of deaths
Public	Reduction of environmental costs (E)	$B^i_E(t)$	Amount of noise Amount of air pollution

Note: i = intervention strategy; t = unit of time.

stakeholders of a reference intervention strategy (Equation (1)).

$$TB_i = \int_0^T \left(B^i_M(t) + B^i_{TT}(t) + B^i_{VO}(t) + B^i_D(t) + B^i_A(t) + B^i_E(t)\right) \cdot e^{-\gamma t}\mathrm{d}t \tag{1}$$

where TB_i is the total benefits of intervention strategy I; 0 is the start of the investigated time period; T is the end of the investigated time period; and γ is the discount rate. The meaning of other variables is explained in Table 1.

When the benefits of intervention strategies are seen as the differences in costs, C, that would be incurred by following intervention strategy i and those that would be incurred by following the reference intervention strategy, R, Equation (1) becomes:

$$TB_i = \int_0^T \left(\left(C^R_M(t) - C^i_M(t)\right) + \left(C^R_{TT}(t) - C^i_{TT}(t)\right) + \left(C^R_{VO}(t) - C^i_{VO}(t)\right) + \left(C^R_D(t) - C^i_D(t)\right) + \left(C^R_A(t) - C^i_A(t)\right) + \left(C^R_E(t) - C^i_E(t)\right)\right). e^{-\gamma t}\mathrm{d}t \tag{2}$$

3. Methodology

Since roads deteriorate over time due to their exposure to the environment and to use, it is necessary to maintain them to ensure that they continue to provide an adequate level of service. An adequate level of service is ensured through the timely performance of interventions. There are many possible intervention strategies that can provide an adequate level of service and they all have different costs and benefits. In order to be able to determine the optimal preservation intervention strategy from the many different acceptable ones it is necessary to determine both the total costs and the total benefits of each.

In the past numerous researchers have investigated optimal interventions strategies for pavement interventions, including Lamptey *et al*. (2008) who studied optimal pavement intervention strategies taking into consideration the owner costs of intervention and the user costs during intervention and Labi and Sinha (2005) who studied the cost effectiveness of various levels of pavement intervention, measuring effectiveness as the increase in service life and taking the owner and user costs during intervention into consideration, as well as Al-Mansour and Sinha (1994), Geoffroy (1996) and O'Brien (1989). In 2009 a comparison of methods for evaluating pavement interventions was conducted (Khurshid *et al*. 2009) which, among other things, found that the criteria used in determining optimal intervention strategies could be grouped as methods measuring effectiveness, costs only, or costs and benefits.

In comparison to the other methodologies previously investigated or proposed, the methodology presented in this paper encompasses all of the benefits and stakeholders related to the investigated road section, how they are related to pavement condition, and how they change over time. According to the classification proposed by Khurshid *et al*. (2009) it would fall into the costs and benefits category.

The proposed methodology is based on the quantification of basic units consumed/used (e.g. number of days of intervention), produced/caused (e.g. number of accidents) or emitted (e.g. tons of CO_2) on the network over the investigated period of time and assigning a monetary value to each of these units. Such a methodology allows that determining of the monetary value of each of the benefits using utility theory (Keeney and Raiffa 1993) or using comparison techniques such as the analytical hierarchy process (Saaty 2006) and many of the willingness to pay methods, such as opportunity cost methods and contingent valuation methods. The monetary values used in this work were determined from a comparison of values found in national and international literature and were adjusted based on expert opinion for Switzerland where necessary (Hermann *et al*. 2008).

The steps of the proposed methodology to evaluate the total benefits of an intervention strategy are shown in Figure 1. The identification of the states of the road section are required to take into consideration the fundamentally different system behaviour when a preservation intervention is being performed and when no preservation

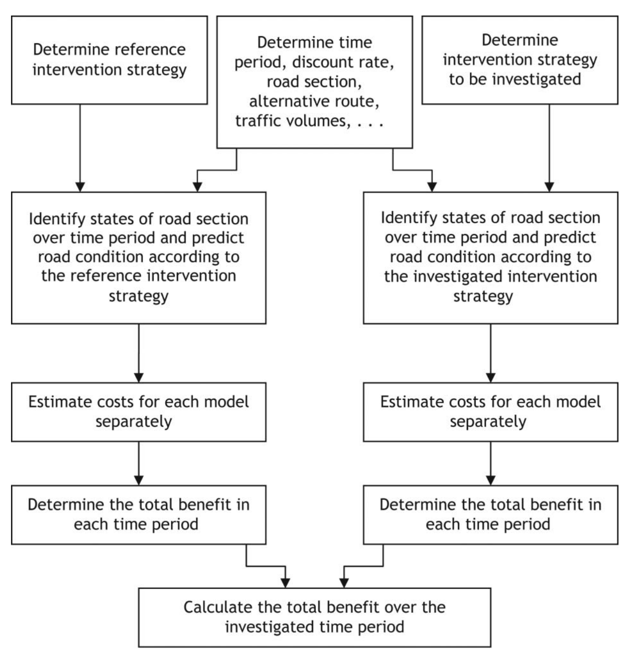

Figure 1. Steps to evaluate the total benefit of an intervention strategy.

intervention is being performed. Two states are often adequate, but for complex preservation interventions that last a relatively long period of time it may be required to have more than two states.

The road condition in Switzerland is approximated based on pavement condition, which is measured using six indices (VSS 2003b). I0 is used to measure surface damage without taking ruts into consideration. I1 is used to measure surface damage taking ruts into consideration. I2 is used to measure longitudinal unevenness. I3 is used to measure transversal unevenness. I4 is used to measure surface friction. I5 is used to measure the load carrying capacity of the road section.

4. Cost models

In general it is proposed to approximate costs by estimating the relevant units, such as road section length upon which each vehicle travels (s), daily traffic volume (DTV), travel time per vehicle (t), and number of people affected (p), and multiplying them by the appropriate unit costs. Two sets of basic cost models (q) are proposed in this section. One set is to be used between preservation interventions, i.e. when no preservation intervention is being performed ($q = 1$) and the other is to be used during preservation interventions, i.e. when a preservation intervention is being performed ($q = 2$). All important roads onto which vehicles may be deviated during an intervention are to be taken into consideration, as well as the percentage of vehicles deviated on to them, in the estimation of all benefits. The elasticity of traffic demand should also be taken into consideration. Example suggested unit costs to be used in Switzerland for each model are given in each section. These are based on values found in national and international literature and adjusted using expert opinion. Details with respect to their determination can be found in Herrmann *et al.* (2008). All costs are given in 2007 Swiss Francs.

4.1. Maintenance costs

Maintenance costs are defined as all costs to the owner of performing interventions, e.g. the cost of labour and material, that prevent or impede deterioration or improve the road up to, but not beyond, its original condition. Maintenance costs are considered to be composed of routine maintenance costs (C_{RM}) and preservation costs (C_p) (Equation (3)). Routine maintenance costs, which are defined in the introduction, are assumed to be incurred between, but not during, preservation interventions and vary directly as a function of road condition. Preservation costs, which are also defined in the introduction, are assumed to be incurred during preservation interventions. The equations proposed to be used to estimate maintenance costs, C_M, between ($q = 1$) and during preservation interventions ($q = 2$) are:

$$C_{Mq} = \begin{cases} C_{RM} \cdot C_{RM}^F(I_1) \cdot s, & q = 1 \\ C_p, & q = 2 \end{cases} \tag{3}$$

where C_{RM} is the routine maintenance costs when $I_1 = 3$; $C_{RM}^F(I_1)$ is a routine maintenance cost factor which varies as a function of I_1 as:

$$C_{RM}^F(I_1) = \begin{cases} 1/3 & \text{for } I_1 \in [0, 1) \\ 1/3 \cdot I_1 & \text{for } I_1 \in [1, 3) \\ 25/12 \cdot I_1^2 - 73/6 \cdot I_1 + 75/4 & \text{for } I_1 \in [3, 5) \end{cases} \tag{4}$$

Due to limited available relevant data, the relationship between the routine maintenance costs and pavement condition was determined based principally on the experience and opinion of a number of experts in Switzerland who are routinely involved in making predictions of maintenance costs. It was determined as follows:

- The mean costs C_{RM} as reported in Müller (2005) were assumed to be associated with the mean condition of cantonal roads in Switzerland $I_1 = 3$ (Bürgi 2002, Hufschmid 2002).
- The maintenance costs when the pavement is in excellent condition ($0 \leq I_1 < 1$) were set at one third of the mean based on cantonal experience in Switzerland (Goebbels *et al.* 2008) taking into consideration, for example, that there will be some damage that must be repaired due to accidents or plowing in winter that occurs regardless of road condition.
- It was then assumed in the absence of information in literature that the routine maintenance costs for fairly good pavement conditions increase linearly between ($1 \leq I_1 < 3$).
- The maintenance costs when the pavement is in very poor condition ($I_1 = 5$) were set to be 10 times higher than for roads in sufficient condition ($I_1 = 3$), based on the work of Hufschmid (2002).
- The quadratic increase in maintenance costs between when the pavement condition is $3 \leq I_1 \leq 5$, was established based on the non-linearity in maintenance costs over this range reported by Hufschmid (2002). This non-linear increase is meant to take into consideration the non-linear increase in routine maintenance interventions, such as the repairing of pot holes, which are required simply to maintain the minimal acceptable service level, over this range.

4.2. Travel time costs

Travel time costs are the costs of travelling in terms of time lost. There is a distinction made between lost time that would have been used for a productive activity and lost time that would have not been used for a productive activity. They are assumed to be carried by the user. Some of the difficulties involved in determining the relationship between pavement condition and travel time costs are:

- The relatively few tests that have isolated the road condition in the evaluation of its impact on vehicle speed.
- The continuous variation of speed along a road section, due to multiple factors, such as traffic behaviour, making it relatively difficult to obtain isolated information about speed and condition at exactly the same location.
- The dependency of vehicle speed on road geometry, making comparisons between the studies published in literature virtually impossible.

Acknowledging these difficulties, the base model proposed for the estimation of travel time costs is shown in Equation (5). The costs vary indirectly as a function of pavement condition, i.e. pavement condition affects the speed of driving, and therefore, the amount of time required to complete a specific trip, once certain road condition thresholds have been reached. These thresholds are defined per road category. The relationship between speed and pavement condition was principally determined based on the results in (Bennett and Greenwood 2001); one of the most complete studies in this area. I_2 was considered to be an adequate representation of pavement condition for the estimation of travel time costs. The travel time costs C_{TT} are calculated as:

$$C_{TTq} = UC_{TTq} \cdot t_q \cdot DTV_q, \quad q = 1, 2 \tag{5}$$

where UC_{TT} is the unit cost of travel time per vehicle

$$t_q = \frac{s}{\mathrm{v}^{\mathrm{q}}_{\mathrm{tech}}}\left(1 + \alpha\left(\frac{u_q}{cap_q}\right)^{\beta}\right) \tag{6}$$

where α is the parameter dependent on road characteristics (0.15 suggested; Lee and Machemehl 2005); β is the parameter dependent on road characteristics (4.0 suggested; Lee and Machemehl 2005); cap is the road capacity, expressed as number of vehicles per unit time; u is the traffic flow during analysed interval, calculated as

$$u = \gamma \times DTV \tag{7}$$

where γ is the percentage of daily traffic that occurs during the analysed time unit; v_{tech} is the free flow traffic speed, which can be calculated as

$$v^q_{tech} = \min\left(v_{\mathrm{Signal}},{}^q\, v^q_{\mathrm{Rough}}\right), \tag{8}$$

where v_{Signal} is the posted speed limit, i.e. it is assumed that the driver travels at the maximum posted speed limit if there is no congestion; and v_{Rough} is the adjustment of the free flow speed, which is dependent on the pavement condition and calculated as:

$$v_{\mathrm{Rough}} = \begin{matrix} v_{\mathrm{Signal}} - a\frac{I_2 - b}{c} & \text{when } I_2 \geq b \\ v_{\mathrm{Signal}} & \text{when } I_2 < b \end{matrix} \tag{9}$$

where a is the speed penalty per IRI unit[1] which is dependent on road and vehicle type (2.3 suggested); b is the speed reduction starting when IRI is higher than 5 m/km (Table 2) (Bennett and Greenwood 2000); c is the factor which gives the degree with which an I_2-Index point per IRI-unit is to be penalised (Table 2) (Bennett and Greenwood 2000)[2].

The unit costs suggested for freight transport are 15.60 CHF/vehicle-hour for the vehicle and 19.70 CHF/person multiplied by the number of passengers per vehicle (VSS 2007). The unit costs suggested for passenger traffic are 19.70 CHF/person, multiplied by the average number of passengers per vehicle (VSS 2003c). Assuming an occupancy rate of 1.57 persons per car, the unit costs equal 30.93 CHF/vehicle-hour for passenger transport.

4.3. Vehicle costs

Vehicle costs are the costs of maintenance and operation of a vehicle. The costs of vehicle operation are principally comprised of fuel costs. The costs of vehicle maintenance include the cost of the man-hours needed for maintenance work and the cost of the materials required, e.g. tyres and brake pads. Some of the difficulties involved in determining vehicle costs are that:

- vehicles are driven over many different roads in many different conditions, making it difficult to link costs to road condition,
- vehicle costs depend significantly on driver behaviour, which in turn depends on the traffic volume and behaviour,

Table 2. Suggested values of b and c as a function of road type.

Road type	b	c
Highway	4.2	0.6
Main rural road	3.7	0.7
Secondary rural road/city road	3.2	0.6

- vehicle costs depend significantly on road geometry, including the slope, curvature, and road width, and
- vehicle efficiency changes over time and varies between vehicles, making it difficult to compare the results of studies conducted in different countries over different periods of time.

In the base model proposed, vehicle costs are grouped as fixed costs, i.e. costs that can be approximated per time unit travelled, and variable costs, i.e. costs that can be approximated per travelled distance unit, or per unit of fuel consumed. The fixed costs are indirectly dependent on road condition, since road condition affects the speed of travel and, therefore, travel time. The variable costs are directly dependent on pavement condition, principally through the longitudinal unevenness of the road (LTNZ 2006) and (Pichler 1981). Combining the fixed costs and the formula for estimation of the variable costs as proposed by (Pichler 1981) the vehicle costs can be modelled as in Equation (10).

$$C_{Vq} = DTV_q \cdot \left(t_q \cdot UC_{VH} + \left(\frac{13 I_2}{800} + \frac{787}{800} \right) \cdot (s_q \cdot (UC_{Vkm} + T_{vq} \cdot UC_f)) \right), \quad q = 1, 2 \qquad (10)$$

where C_V is the vehicle costs; UC_{VH} is the unit vehicle costs per hour driven; UC_{Vkm} is the unit vehicle costs per kilometre driven; T_v is the fuel used per kilometre at the driven speed; UC_F is the unit cost of fuel;

$$\left(\frac{13 I_2}{800} + \frac{787}{800} \right)$$

is an empirically derived factor to take into consideration that the vehicle costs depend on the distance travelled and that fuel consumption over this distance depends on the longitudinal unevenness of the road (Pichler 1981). The value of this factor is between 0.984 and 1.065 (Pichler 1981).

The suggested cost values are given in Table 3 (ASTRA 2003). The relationship between travel speed and fuel consumption is shown in Figure 2 (Keller and Zbinden 2004).

Table 3. Suggested unit costs for the determination of vehicle costs.

Unit cost	Unit	Passenger vehicle	Truck
UC_{VH}	[CHF/h]	1.91	6.16
UC_{Vkm}	[CHF/km]	0.19	0.44
UC_F	[CHF/l]	0.53	0.58

4.4. Discomfort costs

Discomfort costs are the costs of variation in comfort of a travelling individual, both physical, e.g. bruises from an extremely bumpy ride, and psychological, e.g. anxiety due to a perceived increase in the probability of having an accident. They are considered to be carried by the user. The principal difficulty in the estimation of discomfort costs is the high subjectivity of the value of discomfort and the lack of objective measures to determine whether it occurs. For example, the same person could drive over a rough road section today and be very unhappy about the roughness, and tomorrow, with a lot on his mind, not even notice it.

Although various researchers have shown that there is a link between discomfort and the longitudinal unevenness of pavement (e.g. Ihs 2005, LTNZ 2006), there is little indication that there is any variation in driving comfort when the pavement condition is between very good and acceptable ($0 \leq I_2 \leq 3$), which is normally the case in Switzerland, and the values determined for worse pavement condition ($3 \leq I_2 \leq 5$) are widely disputed among experts. It is therefore proposed to estimate discomfort costs C_D, both between and during intervention strategies, as:

$$C_{Dq} = 0, \quad q = 1, 2 \qquad (11)$$

4.5. Accident costs

Accident costs are the costs that result from having an accident, including property damage, injuries and deaths. They are estimated using the accident rate and the cost of each accident when it occurs. The main difficulties in the linking of accident costs to pavement condition is that the majority of accidents depend principally on driver mistakes (Cleveland 1987, Henry 2000, Bester 2003, Stütze 2004, Noyce

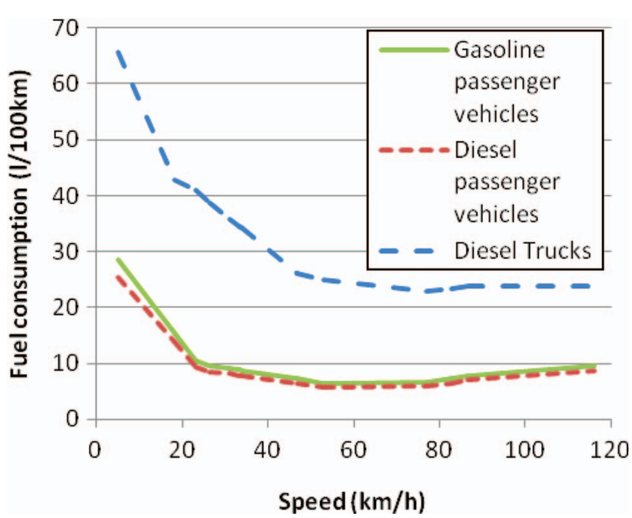

Figure 2. Suggested values of fuel use as a function of speed.

et al. 2005) and pavement condition only has an impact on their ability to correct these mistakes once they are made, for example through shortening the breaking distance. It is also complicated by the fact that the increases in friction and decreases in unevenness sometimes result in higher accident rates (Cleveland 1987, Hauer 1997, Schandersson 1994, McLean 1995, Bester 2003).

Taking into consideration the multitude of research in this area, it is proposed to estimate accident costs as shown in Equation (12), where they are assumed to vary directly as a function of road condition. The relationship between the accident rate and road condition was determined based principally on the results in (NRPA 1997, ASTRA 2003, Ihs 2004, Keller and Zbinden 2004, Stütze 2004). It is considered that accident costs are partially carried by the user (e.g. the value of a temporary or permanent disability to the user, often measured as willingness to pay to avoid injury) and partially carried by society (e.g. the value of a temporary or permanent disability to society, often measure in terms of lost economic output). The accident costs C_A are calculated as:

$$C_{Aq} = \sum_{i=1}^{I} (\theta_{iq}(I_4) \cdot UC_i \cdot DTV_q \cdot s_q \cdot \psi), \quad q = 1, 2 \tag{12}$$

where $\theta(I_4)$ is the rate of occurrence of specific damage type dependent on road condition when no intervention is being performed. It is approximated using the I_4 measure of surface friction and road type (suggested values for highways are given by and shown in Equations (13) to (15) (Stütze 2004)), suggested values for inside and outside city limits are given in Table 4),

$$\theta_{propertyq}(I_4) = 0.4. \frac{67}{99.8541 + 46.572 \cdot \ln(0.00981 \cdot I_4^2 - 0.1081 \cdot I_4 + 0.5966)} \tag{13}$$

$$\theta_{injuriesq}(I_4) = 0.16. \frac{67}{99.8541 + 46.572 \cdot \ln(0.00981 \cdot I_4^2 - 0.1081 \cdot I_4 + 0.5966)} \tag{14}$$

$$\theta_{deathsq}(I_4) = 0.0030. \frac{67}{99.8541 + 46.572 \cdot \ln(0.00981 \cdot I_4^2 - 0.1081 \cdot I_4 + 0.5966)} \tag{15}$$

where i is the type of damage, either property damage, injuries and deaths; UC_i is the unit costs of damage (suggested values are given in Table 5 (ASTRA 2003); and ψ is a correction factor to take into consideration the effect of the work site while performing an intervention ($q = 2$). For $q = 1$ ψ equals 1.

4.6. *Environmental costs*

Environmental costs are considered to be made up of noise costs, C_N, air pollution costs, C_{AP}, and climate costs, C_C, and are calculated as:

$$C_E = C_N + C_{AP} + C_C. \tag{16}$$

4.6.1. *Noise costs*

Noise costs are costs due to the disturbance of persons through excessive noise. Examples of this disturbance are headaches, high blood pressure and sleep problems. In extreme cases the disturbance could even be

Table 4. Suggested values of $\theta(I_4)$.

	$\theta(I_4)$ per 1 Mio. vehicle-km					
	Inside city limits			Outside city limits		
I_4	Property	Injuries	Deaths	Property	Injuries	Deaths
0.0–1.5	2.20	0.92	0.0098	0.70	0.4100	0.0138
1.5–3.0	2.75	1.15	0.0123	1.05	0.5125	0.0173
3.0–4.0	5.50	2.30	0.0246	2.10	1.0250	0.0346
4.0–5.0	8.80	3.68	0.0392	2.80	1.6400	0.0552

Table 5. Suggested values of unit costs of damage.

Damage type	Symbol	Suggested amount CHF	User cost	User cost CHF	Public cost CHF
Property damage	UC_1	45,100	70%	31,570	13,530
Injuries	UC_2	293,500	80%	234,800	58,700
Deaths	UC_3	3,645,000	85%	3,098,250	546,750

psychological illness. They are mainly composed of rolling noise and motor noise. Some of the difficulties involved in the estimation of noise costs include the fact that they are not directly quantifiable. Their quantification requires the consideration of such things as:

- The variation of rental prices, which vary due to many different and difficult to isolate factors.
- The noise attributed health costs, which many also occur due to many different and difficult to isolate factors.

It is assumed that noise costs are borne by the public and it is proposed that they be estimated as shown in Equation (17). Since the main factors affecting noise are the speed of the vehicles and the type of pavement, they are assumed not to vary directly as a function of road condition.

$$C_{Nq} = p_q * UC_{dBAq} * L_{eqq}, \quad q = 1,2 \tag{17}$$

where p_q is the number of affected persons, i.e. the number of persons that live and/or work near the road section and experience high noise levels (e.g. over 55dB(A) during day-time and over 45 dB(A) during night-time); L_{eq} is the equivalent continuous sound level for a road section, with respect to traffic generated sound events, which is calculated as given in (EMPA, 1997):

$$L_{eq} = 10\log\left(\frac{1}{K}\sum_{j=1}^{2}\left(Fz_j 10^{0.1L_j}\right)\right), \tag{18}$$

where Fz_j is the number of each vehicle type/hour; K is the capacity of the road (vehicles/hour); j is the indicator of vehicle type, either passenger car (PC) or truck (T); L_j is the sound level per vehicle type, and is calculated as given in (EMPA 1997):

$$L_j = 10\log\left(10^{\frac{L_{jA}+\Delta L_S}{10}} + 10^{\frac{L_{jR}+\Delta L_B}{10}}\right) \tag{19}$$

where B is the pavement type; ΔL_B is the change in roll noise per pavement type (suggested values given in Table 6); ΔL_S ($L_{\downarrow S}$ is the change in motor noise per slope category (suggested values given in Table 6); L_{jA}

Table 6. Suggested values of the correction factors pavement types and slopes

Pavement type	ΔL_B	Slope	ΔL_s
Melted asphalt	+0	g%, where g > 0	0.8 g
Concrete	+3	g%, where g < 0	0
Pavement	+8		
Drained asphalt	−5		

is the motor noise for vehicle type j, for passenger vehicles calculated as:

$$L_{PCA} = 62.7 + 10\log\left(1 + \left(\frac{v}{44}\right)^{3.5}\right) \tag{20}$$

and for trucks calculated as:

$$L_{TA} = 76.9 + 10\log\left(1 + \left(\frac{v}{56}\right)^{3.5}\right) \tag{21}$$

L_{jR} is the roll noise for vehicle type j, for passenger vehicles calculated as:

$$L_{PCR} = 9.5 + 35\log(v), \tag{22}$$

and for trucks calculated as:

$$L_{TR} = 18.5 + 35\log(v), \tag{23}$$

where S is the slope category; v is the speed; UC_{dBA} is the cost per decibel, per person.

It is noted that the cost per dB(A) per person over a threshold value of 55 dB(A) is set to 115 CHF/Pers/dB(A). This value corresponds to a cost of 15.80 CHF/1000 vehicle-km (ASTRA 2003, ECOPLAN *et al.* 2004). This can also be expressed by vehicle type, i.e. $K_{dBAPC} = 109\ CHF$ for passenger vehicles and $K_{dBAT} = 165\ CHF$ for trucks.

4.6.2. *Air pollution costs*

Air pollution costs are those that are related to the damage caused directly by polluted air, such as health problems and the impact on plant growth. Air pollution is caused by the emissions of vehicles travelling on the road network and in the equipment required to perform preservation interventions, when they burn fossil fuels. These emissions include carbon, nitrogen, water, carbon monoxide, aldehydes, nitrogen dioxide, sulphur dioxide and polycyclic aromatic hydrocarbons. It is assumed that air pollution costs are borne by the public. Some of the difficulties involved in estimating air pollution costs include:

- The determination of the number of people and plants affected by the air pollution, as the transport of air pollution is heavily dependent on the global weather system which results in wide variations in the distribution of air pollution on a daily if not hourly basis.
- The impact of the air pollution on human health and plant growth, as the way living organisms react to changes in emission concentrations varies significantly from human to human and plant to plant.

Despite being an imperfect representation the amount of PM10 emissions is used to take into consideration the many different emissions included in air pollution. The air pollution costs, C_{AP}, are modelled as consisting of two parts as shown in:

$$C_{APq} = C^{FZ}_{PM10q} + C^{E}_{PM10q}, \quad q = 1,2 \tag{24}$$

where C^{FZ}_{PM10q} is the costs of the $PM10$ emissions by vehicles travelling on the road network, which are taken as dependent on fuel usage and therefore varies directly as a function of the speed driven and hence indirectly as a function of road condition, measured using the indicator for longitudinal unevenness. They are calculated as:

$$C^{FZ}_{PM10q} + s_q \cdot DTV_q \cdot \sum_{w=1}^{W} \left(\mu_{wq} \cdot T^{w}_{v} \cdot \frac{UC^{w}_{PM10}}{T^{w}_{avg}} \right), \quad q = 1,2 \tag{25}$$

where μ_W is the percentage of vehicles of each type (w); T^{w}_{avg} is the fuel used on average by vehicle type (l/100 km) (suggested values are 29.1 l/100 km for trucks, 7.7 l/100 km for passenger vehicles with diesel motors, and 8.6 l/100 km for vehicles with gasoline motors); T^{w}_{v} is the fuel usage per vehicle type (litres/100 km), which is dependent on the speed, v; UC^{w}_{PM10} is the average unit cost of air pollution per vehicle type (CHF/vehicle-km); and C^{E}_{PM10q} is the costs of PM_{10} emissions by equipment used during the performing of preservation interventions, which are taken as dependent on the intervention

$$C^{E}_{PM10q} = \begin{cases} 0 & q = 1 \\ C_{p-o} \cdot UAP_{Cp-o} \cdot UC^{E}_{PM10} & q = 2 \end{cases} \tag{26}$$

where $C_{p\text{–}o}$ is the owner cost of the preservation intervention (CHF); $UAP_{Cp\text{–}o}$ is the unit of air pollution per owner cost of preservation intervention (ton/CHF) (suggested values are given in Table 7 (ECOPLAN 2007)); UC^{E}_{PM10} is the unit cost of emissions (CHF/ton).

The suggested value for UC^{E}_{PM10}, is 28,675 CHF/ton. The suggested values for UC^{PC}_{PM10} and UC^{T}_{PM10} are, 0.0231 CHF/vehicle-km, 0.1474 CHF/vehicle-km, respectively (ECOPLAN 2006, ECOPLAN 2007). The suggested values for worksite emissions, estimated as a percentage of the owner cost of the intervention are given in Table 7.

4.6.3. Climate costs

Climate costs are those that are related to the damage caused indirectly by polluted air, i.e. through the changing of the climate which in turn may adversely affect humanity. Climate change is expected to occur predominantly through the emission of CO_2 into the atmosphere. CO_2 is emitted into the atmosphere through the burning of fossil fuels. Some of the difficulties involved in estimating climate costs include the modelling of:

- the impact of emissions on the environment, and
- the evaluation of the severity of this impact on humans.

The simple model proposed to estimate climate costs is based on fuel consumption, which is affected by pavement condition through its impact on vehicle speed (Section 4.2). Any negative impact on the climate of performing an intervention is then taken into consideration through the additional fuel consumption while performing the interventions, for example from the stopping and starting of vehicles. If there is reduction in fuel consumption while performing an intervention, for example due to the reduction of speed of vehicles, there will be a climate benefit. It is assumed that climate costs are carried by the public. The climate costs C_C are calculated as

$$C_C = S_q \cdot DTV_q \cdot \left(\sum_{w=1}^{W} \mu_{wq} \cdot T^{w}_{vq} \cdot \gamma_{wq} \right) \cdot UC_{CO_2}, \quad q = 1,2 \tag{27}$$

Table 7. Suggested worksite emissions for the evaluation of interventions.

Emission source	Tons PM_{10} per Mio. CHF of intervention
Engines of equipment used on the worksite	0.085
Dust from the worksite	0.104
Transport to and from the worksite	0.018
Total	0.207

where UC_{CO_2} is the unit cost of CO_2 (CHF/ton) (suggested as 50 CHF/ton); μ_w is the percentage of vehicles of each vehicle type; T_v^W is the fuel consumption of a vehicle of vehicle type W, which is dependent on speed (l/100 km); γ_w is the ratio of kg CO_2 per litre fuel determined per vehicle type (suggested as 2.647 kg/l for diesel vehicles and 2.404 kg/l for gasoline vehicles).

5. Example

To illustrate how the proposed methodology and base costs models can be used to evaluate interventions and to determine optimal intervention strategies an example was done for a representative road section in Switzerland. The example problem is to determine the intervention strategy that maximises total benefit over the next 75 years for a road section where road users have two possible detours when an intervention is being performed. The basic information with respect to each is shown in Table 8.

It has been predetermined that the intervention strategy selected should consist only of partial depth resurfacing interventions with reinforcement that will use cold milling in the removal of approximately 85 mm of the surface layer. Each intervention, when an intervention is performed, will last 4 months and is performed between the 1st of May and the 31st of August in the year it is executed. The intervention will improve the deterioration indices of I_1 to 0, I_2 to 0.5 and I_4 to 0.5 regardless of the values of the deterioration indices at the time of intervention (Gnehm 2008), but does not alter the deterioration rate, i.e. deterioration continues at 0.12 units per year. A discount rate of 2% is used.

5.1. *Optimisation*

The general mathematical formulation of the optimisation problem is given in Equation (28).

$$Max. \sum_{a=1}^{A} \left(TB_a^{Max}\right) \cdot y_a \tag{28}$$

where a is the number of interventions included in intervention strategy; A is the maximum number of interventions to be considered; TB_a^{Max} is the maximum total benefit if only a interventions are performed; and y_a is a binary variable.

5.2. *Analysis*

Using the equations presented in the article and exhaustive enumeration, the optimal intervention strategy was determined to be to perform interventions, i.e. a partial depth resurfacing with reinforcement in year 26 and 51 for a total benefit of 9.92 million CHF (Table 9, indicated as Intervention Strategy 2 Int). This strategy will result in additional costs for the owner of 0.19 million CHF and reduced costs for the user and for the public of 9.09 million CHF and 1.02 million CHF, respectively. Table 9 shows the absolute costs estimated for the reference (0 Int.) and the optimal intervention strategy (2 Int.), and the benefit of the optimal intervention strategy, i.e. the

Table 8. Example: Basic information.

Variable	Investigated road section	Detour 1	Detour 2
Length (m)	1006	6700	11,000
Width (m)	10.5	N/A	N/A
Number of lanes	2	4	2
Speed limit (km/h)	70	120 kph	50 kph
I values	Decreases from initial values at 0.12 units per year	2	2
Average daily traffic in 2010	18,700	*	*
Growth in average daily traffic per year	2% of 2010 ADT	2% of 2010 ADT	2% of 2010 ADT
Traffic capacity/day	50,000	**	**
Percentage of passenger vehicles	80	N/A	N/A
Percentage of trucks	20	N/A	N/A
Routine maintenance cost/km/year (CHF)	3500	N/A	N/A
Persons affected by excessive noise levels in 2010	100	50	50
Growth in persons affected by noise	2 people per year (2% of 2010 value)	1 person per year (2% of 2010 value)	1 person per year (2% of 2010 value)
Traffic deviated during intervention	10% of vehicles choose to take detours	1% of deviated vehicles	9% of deviated vehicles

Notes: *Assumed to be sufficiently low with respect to traffic capacity that free flow traffic exists even with the addition of detoured vehicles. **Assumed to sufficiently high with respect to the traffic flow with detoured vehicles to allow free flow traffic to occur.

Table 9. Example: Absolute cost and benefits of reference and optimal intervention strategies.

			Absolute costs/benefit ($\times$ 10^6 CHFs)					
			Owner	User		Public		
Intervention Strategy Type	Year(s) of Intervention	Absolute cost or benefit	Maintenance	Travel Time	Vehicle	Accident	Environmental	TOTAL
0 Int.	0	Cost/cost type	0.53	168	133	37	44	383
		Cost/stakeholder	0.53	330		52		
2 Int.	26, 51	Cost/cost type	0.72	166	130	32	44	373
		Cost/stakeholder	0.72	321		49		
		Benefit/cost type	−0.19	2.14	2.54	5.66	−0.23	9.92
		Benefit/stakeholder	−0.19	9.09		1.02		

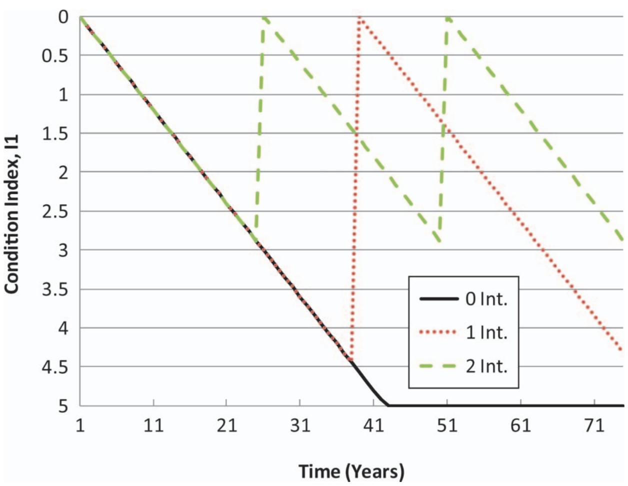

Figure 3. Example: Expected values of the deterioration index I1.

absolute costs when the optimal intervention strategy is followed minus the absolute costs when the reference intervention strategy is followed. The expected values of the deterioration indices if the optimal intervention strategy or the reference intervention strategy is followed are shown in Figure 3. The deterioration indices vary between 0.0 and 3.0 when the optimal intervention strategy is followed. The yearly benefits and their distribution by cost type and by stakeholder are shown in Figure 4.

It can be seen from Table 9, that most of the costs related to the investigated road section are incurred by the user (330 and 321 $\times$ 106 CHF for the reference and optimal intervention strategy, respectively). The costs incurred by the public are only 15% of these costs and those incurred by the owner are only 2% of these costs. As most of the costs are incurred by the user so are most of the benefits that result from the choice between intervention strategies (Figure 4). Most of the user benefits when the road section has an I1 $<$ 4 are due to the reduction in vehicle and accident costs when

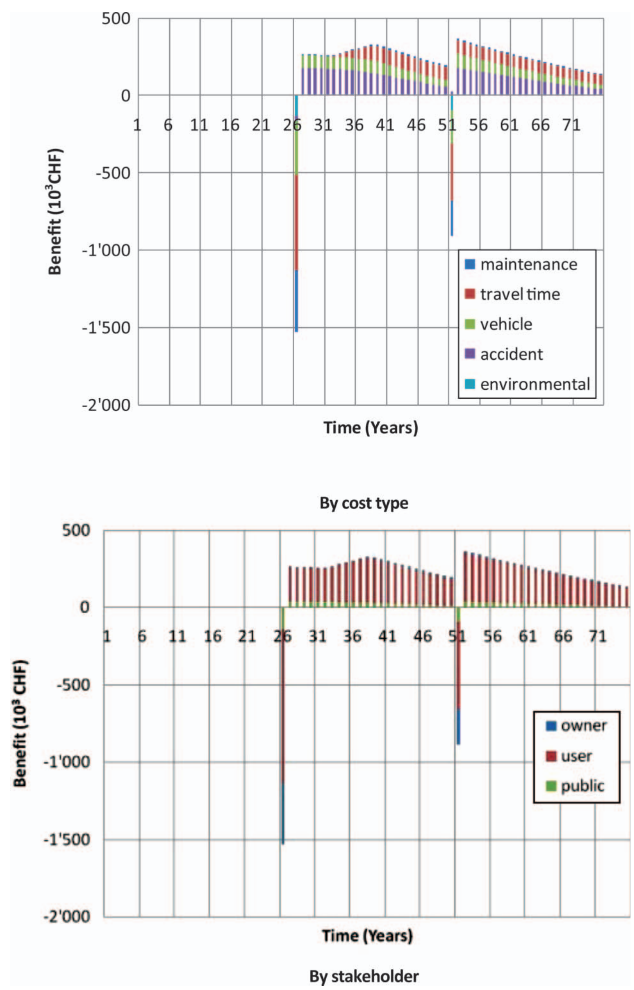

Figure 4. Example: Discounted yearly benefits and their distribution when the optimal intervention strategy is followed.

the optimal intervention strategy is followed rather than the reference strategy. Once I1 $>\ =4$ the further deterioration of the road condition that would occur when following the reference strategy leads to increasing benefits due to the reduction in travel time costs.

This occurs because with I4 values higher than or equal to 4, as in the reference strategy, vehicles must reduce their speed significantly from the posted limit, and therefore any improvement of I4 results in benefits due to the reduction of travel time costs.

The performance of interventions results in a substantial increase in costs for all stakeholders in the years of intervention and in an increase in the costs of almost all cost types (Figure 4). The one exception is the reduction in accident costs during the year of the second intervention. This occurs because there are more accidents when the road section has an I1 value of 5 for 12 months (the reference strategy) than when the road section has an I1 value of 2.9 for 4 months, has an intervention for four months in which the number of accidents increases, and has an I1 value of 0 for 4 months (the optimal intervention strategy). The exact distribution of costs and costs per stakeholder during each intervention included in the optimal intervention strategy are shown in Figure 5.

5.3. *Stakeholder significance*

To investigate the significance of taking into consideration the total benefits related to a road section in the determination of optimal intervention strategies, the optimal intervention strategies were determined for two additional cases, taking into consideration

- only owner benefits (Case 1), and
- only owner and user benefits (Case 2).

These cases along with the original, i.e. total benefits are presented together in Table 10.

From Table 10 it can be seen that if only owner benefits are considered, i.e. maintenance benefits, the optimal intervention strategy is to perform one intervention in year 39 resulting in 0.07×10^6 CHF owner benefit and total benefit of 6.96×10^6 CHF (indicated as 1 Int. in Figure 6). The costs of all intervention strategies with two or more interventions are more expensive for the owner than performing one intervention in year 39. In fact, they would cost the owner more than even the reference strategy of doing no preservation interventions and continuing to only perform routine maintenance, even taking into consideration the exponential relation of routine maintenance costs that is expected (Figure 7). The maintenance costs due to the reference strategy increase to 15×10^3 CHF/year but then stay constant

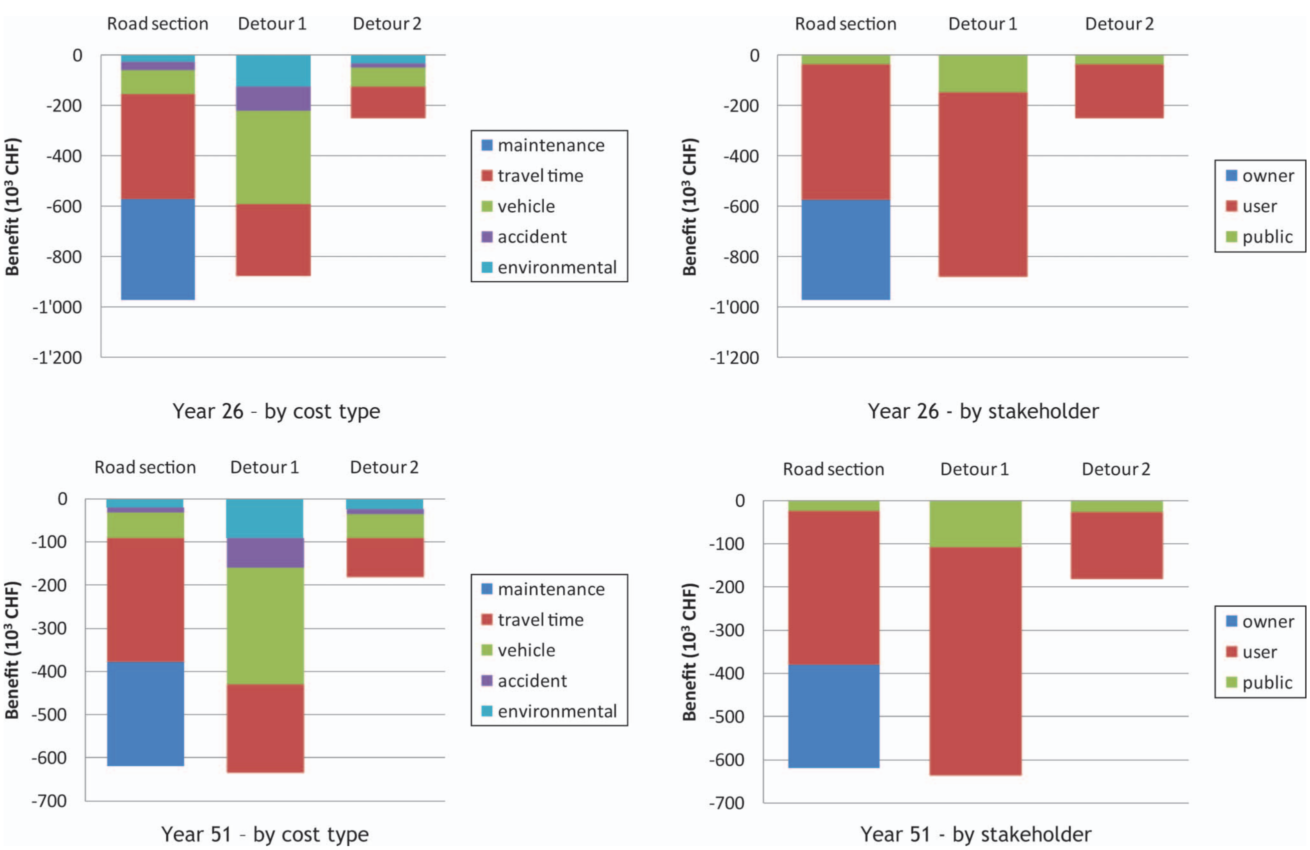

Figure 5. Example: Discounted benefit during interventions when following the optimal intervention strategy.

Table 10. Example: Absolute cost and benefits of the optimal intervention strategies for each stakeholder.

			Absolute costs/benefit ($\times 10^6$ CHFs)					
			Owner	User		Public		
Stakeholder considered	Year(s) of Intervention	Absolute cost or benefit	Maintenance	Travel Time	Vehicle	Accident	Environmental	TOTAL
Owner	39	Benefit/cost type	0.07	2.18	1.63	3.20	−0.11	6.96
		Benefit/stakeholder	0.07	6.30		0.59		
Owner, user	26, 51	Benefit/cost type	−0.19	2.14	2.54	5.66	−0.23	9.92
		Benefit/stakeholder	−0.19	9.09		1.02		
Owner, user, public	26, 51	Benefit/cost type	−0.19	2.14	2.54	5.66	−0.23	
		Benefit/stakeholder	−0.19	9.09		1.02		9.92

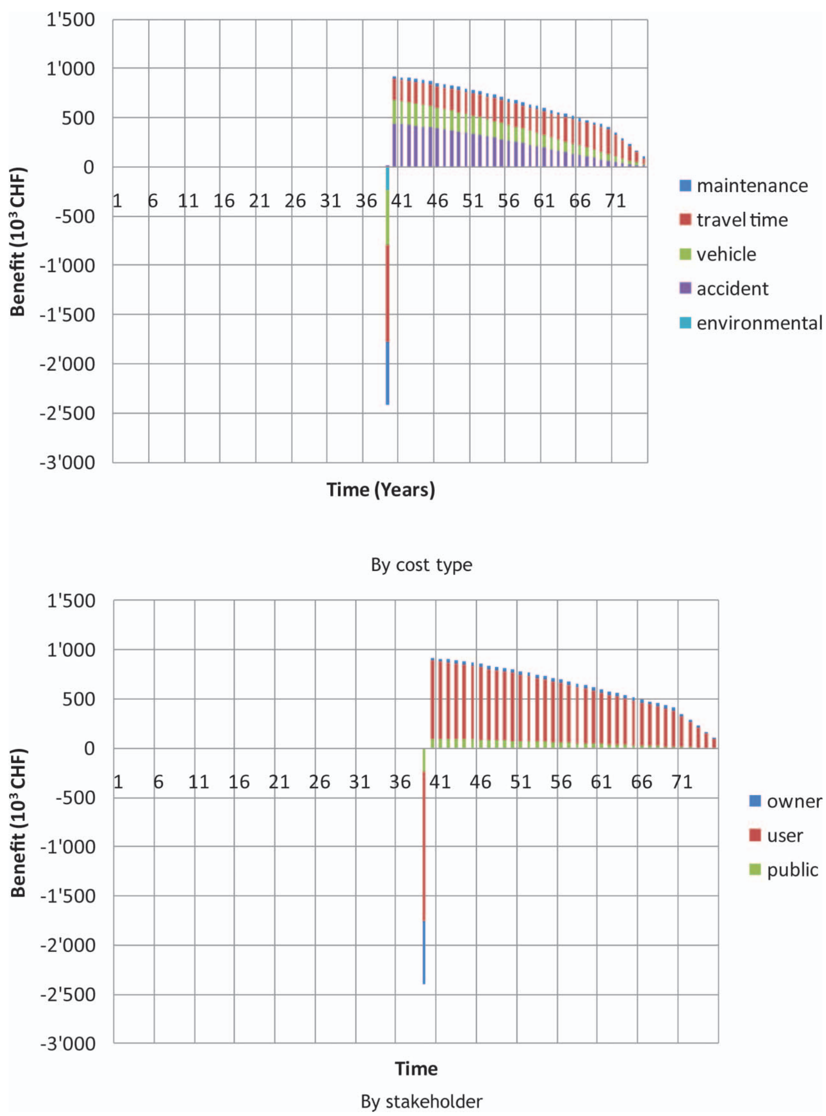

Figure 6. Example: Discounted yearly benefits by cost type and stakeholder when the owner's optimal intervention strategy is followed.

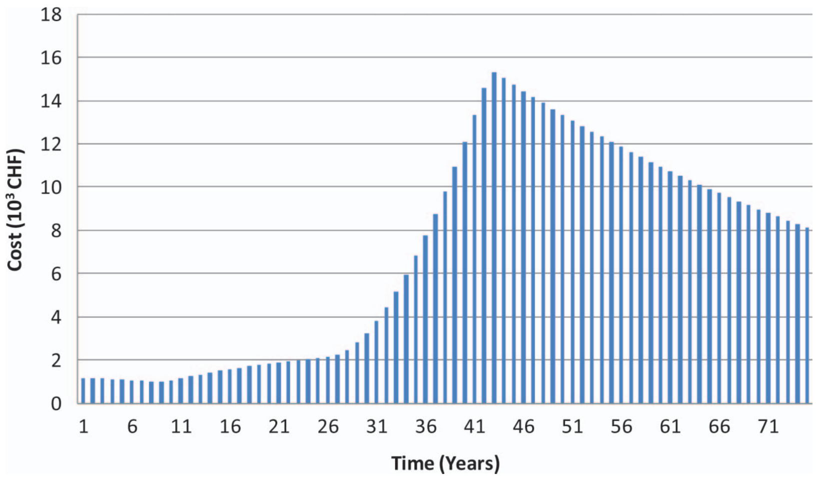

Figure 7. Example: Discounted owner costs when the reference intervention strategy is followed.

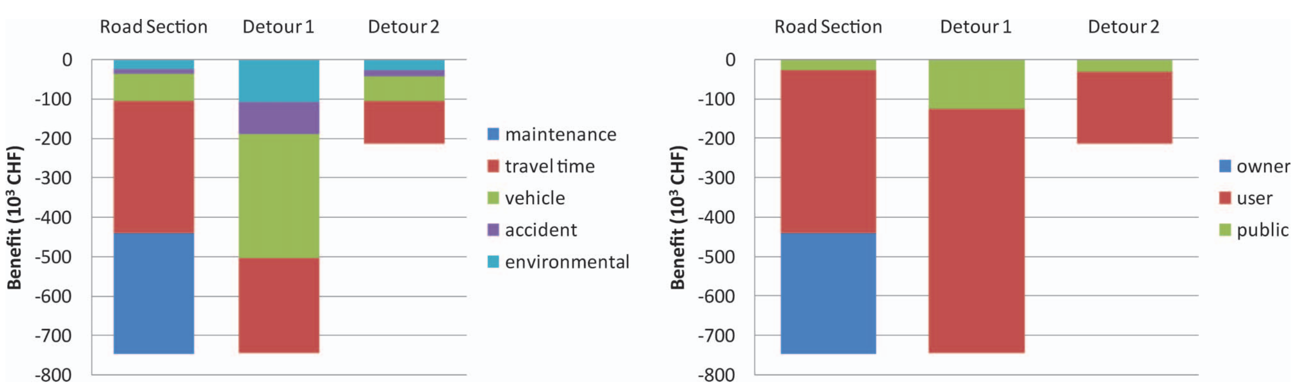

Figure 8. Example: Discounted benefits during intervention of the owner's optimal intervention strategy.

(without discounting). The benefits of executing one intervention in year 39 are shown in Figure 8 (indicated as 1 Int.).

If only owner and user benefits (or only user benefits) are considered, the optimal strategy is the same as when the benefits of all stakeholders are taken into consideration, i.e. to execute interventions in years 26 and 51 (650 $\times$ 10^6 CHF), resulting in a total benefit of 9.92 $\times$ 10^6 CHF. The reason the optimal intervention strategy, and therefore the benefits for each stakeholder, are the same as when the benefits of all stakeholders are considered is due to the large portion of total benefits that are attributable to the user (approximately 90%). In other words, once the optimal intervention strategy for the user is found, the impact of the consideration of the other stakeholders has little impact on the optimality of the intervention strategy. This strategy would also be approximately 120 $\times$ 10^3 CHF more expensive for the owner than the optimal strategy determined considering only owner costs.

It is interesting to note that, in this example, the consideration of user benefits alone is sufficient to determine the optimal intervention strategy. Of course this is because the most significant portion of absolute costs related to the road section is incurred by the user (approximately 85%) and the largest possible reduction in costs is due to the reduction of user costs. Therefore, a 1% reduction in user costs from the reference strategy (3.3 million CHF) is more than six times all the owner costs of the reference strategy.

6. Conclusion

The methodology and models proposed to be used to evaluate the total benefits of road preservation interventions in Switzerland were presented, along with an example of how these relationships can used to determine optimal intervention strategies taking into consideration the total benefit related to a road section.

The models relate benefits to road condition through pavement condition indicators, such as surface friction, surface damage and the longitudinal unevenness, and road type. They have been developed using the natural units of the physical quantities involved, which allows for the changing of their monetary value without modification to the methodology and models. Using the pavement condition information with commonly available information about the road section, such as daily traffic volume, speed limits or number of affected persons, the total benefit can be numerically estimated and attributed to each stakeholder group.

To ensure that the presented methodology and models can be used to accurately evaluate road preservation interventions in Switzerland, it is now necessary to determine the most appropriate values of the physical quantities to be used in the models and to compare predicted results with real world examples. It is also advised that research work be conducted to verify and improve upon the base cost models if necessary.

Notes

1. IRI is the international roughness index. It is a worldwide standard for measuring pavement roughness. The index measures pavement roughness in terms of the number of inches per mile that a laser, mounted in a specialised van, jumps as it is driven across the interstate and expressway system.
2. It is assumed that the relationship between I2 and IRI can be linearly approximated from the difference in the I2 values that correspond to the IRI values between 5m/km and 6 m/km.

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