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ROAD SAFETY AND PAVEMENT MANAGEMENT: A CASE STUDY OF TANZANIA

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Abstract. The implementation of pavement management seems to ignore road safety, with its focus being mainly on infrastructure condition. Safety management as part of pavement management should consider various means of reducing the frequency of vehicle crashes by allocating corrective measures to mitigate accident exposure, as well as reduce accident severity and likelihood. However, it is common that lack of accident records and crash contributing factors impedes incorporating safety into pavement management. This paper presents a case study for the initial development of pavement management systems considering data limitations for 3000 km of Tanzania's national roads. A performance based optimization utilizes indices for safety and surface condition to allocate corrective measures. A modified Pareto analysis capable of accounting for annual performance and of balancing resources to achieve good surface condition and low levels of safety was applied. Tradeoff analysis for the case study found the need to assign 30% relevance to condition and 70% to road safety. Safety and condition deficiencies were corrected within 5 years with the majority of improvements dedicated to surface treatments and some geometric corrections. Large investments for correcting geometric issues were observed in years two and three if more money was made available.

Keywords: road safety, pavement management, optimization, management.

1. Introduction

It is typical for initial implementations of pavement management systems to face shortages of data. Even if an agency has a track record of collected data, it is not rare that at the time of implementation, new needs for data may appear. At such a point two decisions are possible: to collect the required data (extending a few additional years), or to use what is available to obtain a first cut model. Such an initial model is valuable to demonstrate the advantages of implementing a management system, and should be improved as new data becomes available in future periods. In many cases this may go in line with taking advantage of favorable political climate for implementing infrastructure management systems.

Traditionally, initial implementations of road management systems are dedicated to achieve optimal levels of condition while dealing with budget restrictions (Haas *et al.* 1994; Tighe *et al.* 2001). Other important objectives (i.e., mobility, safety, accessibility and social cost) are normally left for a future stage (Feunekes *et al.* 2011). Engineers have historically considered skid resistance as a means to incorporate safety into pavement management (Ong, Fwa 2007). This approach is however, deficient as it lacks of a consideration of the ample full range of factors related to accident likelihood, exposure and severity.

It was a decade ago that a framework with a comprehensive list of factors for a more integral incorporation of road safety was proposed (Tighe et *al.* 2001). Even though such an approach recognized the presence of human, road and vehicle factors when explaining accidents (collisions), it was clear that safety-improvements can only mitigate their impact (Odgen 1996). Current approaches to pavement management, however, only provide direct countermeasures for road factors. Human and vehicle factors can only be mitigated, due to its random nature, by improvements mostly in the form of safety hardware (i.e., guardrail, rumble strip) reducing accidents' severity. In addition, the allocation of safety improvements relies on safety performance of road segments based on observed collisions. In addition one may want to consider other indicators of safety issues not necessarily leading to accidents. Such indicators take the form of conflicts which have the potential to become accidents when the road experience greater traffic volumes or when other factors change (i.e., weak police enforcement) (Road safety manual 2003).

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Several attempts have been made to develop a management framework with a decision making system capable of combining two or more objectives. Computing software such as HDM3 (Watanatada *et al.* 1987) and HERST (FHWA 2009) recognized the need to incorporate several objectives in the analysis, however, their formulation was based on the monetization of all objectives to achieve a common dimension and, their analytical frameworks relied on lifecycle cost-benefit analysis.

This paper uses locally available information on safety hardware to build a safety indicator in order to base initial decisions while data on accident frequencies is collected. This indicator is combined with international roughness index (IRI) to base decisions on funding allocation for the operational and strategic management of a network of pavements. The decision making system applies linear programming to allocate investments on maintenance and rehabilitation actions with the objective of sustaining good levels of safety and condition while constrained by annual budgets. A case study of the Tanzania road network, where limited information was available, is employed to establish a first cut model. This model explicitly considers several individual safety issues and proposes – in the understanding of its limitations – a method capable of balancing dissimilar units which translates into a budget exercise capable of supporting strategic planning. The authors did recognize the need to complement and expand this initial model as new data becomes available in the future (from in service road safety audits).

1.1. Objective

To incorporate road safety into pavement management in the absence of accident frequencies and other traditionally required information.

2. Methodology

2.1. Performance modeling

Pavement Deterioration models used in this study followed traditionally-shaped curves similar to those well documented in the literature (Haas *et al.* 1994, Paterson, Attoh-Okine 1992; Watanatada 1987). For safety, performance models can take the form of a safety index that changes across time (De Leur, Sayed 2002) or a measure that captures the potential for improvement (Anastasopoulos, Mannering 2008; Hauer 1997). The latter considers, the unavoidable amount of accidents related to the randomness of human errors and vehicle failures (El-Basyouny, Sayed 2010) and it serves as a base level in the prioritization of improvements when contrasted with predicted accident frequencies.

An accident database with records of accident's nature, contributing factors and sequence of issues, was not available for Tanzania. Therefore a safety index, based on exposure, severity and accident likelihood (probability) from local observations of existing safety hardware and road condition, was used for this case study as suggested elsewhere (De Leur, Sayed 2002). In the future and once road accidents databases are established, collision frequencies should be correlated with a set of causal factors (fixed, random or variable) for the development of a more refined safety performance model employing conjugated Poisson modeling.

A safety index was based on local assessments of safety hardware and pavement surface condition, each of the safety elements (exposure, severity and likelihood) was given a factor from zero (negligible) to three (deficient) and in some cases up to five (highly deficient) according to the scale used by Tanzania Roads inspectors. All factors were combined by multiplying their individual effects to obtain a final safety index for each segment of the network (Eq (1)). This resulted in a 0 to 27 scale, calibrated to produce safety performance models by fitting traffic progression from very low volume roads to nearly levels of service of saturation (between LOS C and LOS D). Land use was used as a proxy of road's functional classification due to the lack of information on traffic volumes. In Canada some DOTs have used functional classification as a proxy for traffic intensity (Cunningham *et al.* 2010). Therefore a traffic index (V_i) per land use was created; values in the zero to one scale were given to four land uses (Urban, Interurban, Rural, Forest Reserve). Based on this, a combined factor of severity and exposure was obtained by adding such a traffic index with a normalized ratio of length (L), per segment.

$$SI = 27\left(\frac{V_i}{V_{MAX}}\frac{L_i}{L_{MAX}}\right)\left(\frac{S_i}{S_{MAX}}\right)\left[\frac{CF_1}{n}+\cdots+\frac{CF_n}{n}\right], \quad (1)$$

where V_i – traffic volume index of segment i^{th}, vpd; V_{MAX} – max traffic volume index, vpd; L_i – length of segment i^{th}, km; L_{MAX} – max segment length, km; S_i – speed at the i^{th} segment, km/h; S_{MAX} – max speed in the network, km/h. CF_1 to CF_n = contributing factors of likelihood, such as pavement condition, existence of guardrail, road alignment, shoulder or lane width, etc.

2.2. Treatments for safety and condition

Two treatments to correct deficient surface conditions were identified: micro-surfacing (for minor rutting issues) and mill-overaly (to correct major rutting and bleeding). Table 1 summarizes the effectiveness of safety treatments measured by an extension of service life (in gain of years) or gain in safety index, and their cost. It should be noticed that, microsurfacing and mill-and-overlay treatments could be triggered by either objective (safety or condition), their effectiveness in terms of safety are the same because they correct all surface deficiencies. In the absence of local information on cost, each improvement in the model was given a value based on 2007 exchange rate for Canadian dollars to EUR per lane-meter as observed in the province of New Brunswick (Feunekes *et al.* 2011). Three levels of safety index were established (low, medium and high), and the network was segmented accordingly. Low safety index went from zero to three, medium from three to nine and high from nine to twenty seven.

Effectiveness was based on the following assumptions: road realignment will eliminate not only geometric issues but will also correct pavement surface, shoulder and lane deficiencies. Therefore effectiveness of realignment was based on a reset to the base level of the safety index due to the correction of all 6 factors in the likelihood of the model, it should be noticed that this did not reset the safety index to zero because of the presence of random factors as explained before. Any corrections on shoulder or lane width will reset the individual component of safety to zero but only partially improve the overall safety index. Any treatment correcting surface problems (rutting or bleeding) will be treated similarly contributing only partially to reduce the overall safety index. In addition, it will have an effect in pavement condition. Three generic safety improvements were specified in the model (as explained before) in order to account for the existence of other safety issues for which information was unavailable, in addition to future safety deficiencies not currently identified but linked to increases in traffic growth. The three generic improvements obey different levels of required corrections, namely: minor for hardware, medium for surface related treatments and major for realignments or other major investments.

Treatments dedicated to improve pavement condition are presented in Table 2. Effectiveness was modeled by an extension of service life. Reconstruction resulted in a full correction of road safety (including alignment) and rejuvenation of both: structure and surface.

2.3. Optimization model

A multi-objective formulation based on optimization was used for this case study. Detailed mathematical formulations of linear integer programming for condition or safety can be found elsewhere (Li, Madanu 2008; Lytton 1994; Watanatada *et al.* 1987). Eq (2) summarizes the objective and budget constraint for this case study.

Table 1. Treatment effectiveness (Gain in years or in Safety Index) and cost in EUR/m

		Urban Location			Rural Location			EUR/m
	PFI	Low	Medium	High	Low	Medium	High	
ROAD SAFETY IMPROVEMENT	Realignment	Reset to SI_0	Reset to SI_0	Reset to SI_0	Reset to SI_0	Reset to SI_0	Reset to SI_0	394
	Mill and overlay	15 yrs or $\Delta SI = 4.05$	9 yrs or $\Delta SI = 8.10$	3 yrs or $\Delta SI = 8.10$	12 yrs or $\Delta SI = 3.37$	6 yrs or $\Delta SI = 6.75$	3 yrs or $\Delta SI = 6.75$	131
	Micro-surfacing	15 yrs or $\Delta SI = 4.05$	9 yrs or $\Delta SI = 8.10$	3 yrs or $\Delta SI = 8.10$	12 yrs or $\Delta SI = 3.37$	6 yrs or $\Delta SI = 6.75$	3 yrs or $\Delta SI = 6.75$	33
	Widening Shoulder	5 yrs or $\Delta SI = 1.35$	3 yrs or $\Delta SI = 2.7$	1 yrs or $\Delta SI = 2.7$	4 yrs or $\Delta SI = 1.13$	2 yrs or $\Delta SI = 2.25$	1 yrs or $\Delta SI = 2.25$	50
	New Shoulder							99
	Guardrail							41
	Lane Widening							36
	Minor safety issues	5 yrs or $\Delta SI = 1.35$	3 yrs or $\Delta SI = 2.70$	1 yrs or $\Delta SI = 2.70$	4 yrs or $\Delta SI = 1.13$	2 yrs or $\Delta SI = 2.25$	1 yrs or $\Delta SI = 2.25$	33
	Medium safety issues	15 yrs or $\Delta SI = 4.05$	9 yrs or $\Delta SI = 8.10$	3 yrs or $\Delta SI = 8.10$	12 yrs or $\Delta SI = 3.37$	6 yrs or $\Delta SI = 6.75$	3 yrs or $\Delta SI = 6.75$	131
	Major Safety Issues	Reset to SI_0	Reset to SI_0	Reset to SI_0	Reset to SI_0	Reset to SI_0	Reset to SI_0	328

Note: SI_0 – Initial road safety index; ΔSI – gain in safety index. Low, medium, high – Potential for improvement.

Table 2. Treatment effectiveness for pavements (lifespan extension in years) and cost in EUR/m

		Treatment type	AC-High	AC-Low / ST-high	ST-Low	Cost, EUR/m
Condition	Asphalt	Crack sealing	2	3	–	1
		Micro-surfacing	7	8	–	33
		Mill and overlay	9	10	–	131 (per lane)
		Major Rehabilitation	15	22	–	197 (per lane)
		Reconstruction	Back to zero	Back to zero	–	328 (per lane)
	Sealed	Second Seal	–	YR 6	YR 6	9
		Minor Rehabilitation (level and reseal)	–	YR 10	YR 10	17
		Double Seal (pulverize & seal)	–	YR 14	YR 14	30

Note: AC – asphalt; ST – surface treatment; High and Low – intensity of transit; EUR/m – EUR per linear meter.

$$\text{MAXIMIZE } Z=\alpha\sum_{i=1}^{n}\sum_{t=1}^{T}\sum_{j=1}^{J}L_iQ_{itj}+\beta\sum_{i=1}^{n}\sum_{t=1}^{T}\sum_{j=1}^{J}S_{itj}L_i, \quad (2)$$

$$\text{Subject to:} \quad \sum_{i=1}^{n}\sum_{t=1}^{T}\sum_{j=1}^{J}C_{t,j}x_{t,i,j}L_i \le B_t, \quad (3)$$

where α and β – variable weights for the analysis; x – a binary decision variable for safety or condition; Q_{tij} and S_{tij} – condition or safety index of asset i on period t after receiving treatment j; L_i – length of segment i, km; $C_{t,j}$ – unitary cost in EUR/m of treatment j on year t; B_t – annual budget on year t.

This mathematical formulation is complemented with a total enumeration process (Watanatada *et al.* 1987) with arcs connecting paths and nodes recording levels of service (safety or condition) and associated cost in the event that a particular treatment (or none) is selected. This enumeration maps expected consequences of applying each available treatment at each segment of road at each time step and for the length of the analysis. It produces alternative chains of decision variables from which the software selects the optimal in terms of the objective and constraints. Integer linear programming (as herein suggested) or a heuristic method such as evolutionary algorithms may be used to obtain a solution (although the latter approximate).

The formulation herein presented, explicitly incorporates indices from two conflicting objectives instead of monetizing them. A global objective resulting from combining both safety and condition through a weighted sum (Revelle *et al.* 2003) was used to examine the dominance of one over the other by changing the variable weights α and (i.e., different relative importance of the objectives). Results from the previous procedure were used to identify the non-inferior set of possible solutions, further refined using a performance criterion that compares the degree of achievement and capacity to sustain good results across time.

3. Case study

3.1. Portion of the Tanzania road network

Tanzania is a low income country with an estimated road network of 86 000 km (Fig. 1) of which 7% are paved roads. In terms of safety, fatalities reached 2595 in 2007 which translates to 5.8 per 100 000 people (World Bank 2011). For a country with a gross domestic product (GDP) per capita of US $514 (in 2010) this goes in line with the findings of Koptis and Cooper (2005) and Mumford (2011), therefore one can argue that, as the country develops, there is a very high likelihood of reaching levels between 16 and 25 fatalities per 100 000 as predicted by the aforementioned models. This justifies the need to develop a road management system that considers safety, in order to mitigate fatalities and injuries from road collisions.

The first step for the model was to prepare a joint database for safety and condition. Safety data was available in geospatial format, while condition information was available in an *MS-Excel* spreadsheet format. Both databases were merged based on route and link number. The latter produced a subset of records of approximately 3000 km of paved roads (bolded in Fig. 1). In particular they consisted on (a) records of condition: IRI, rut depth, bleeding, raveling, shoulder condition, (b) geometric data: shoulder width, lane width, horizontal and vertical curves, existence of guardrail, (c) other information: land use, pavement surface condition, presence of vegetation and drainage condition. Fig. 1 presents a summary of segment counts per level of deficiency. Deficiency for roughness (IRI) ranged from 0 (none) to 5 (very deficient), for rutting from acceptable (0) to deficient (1) to highly deficient (2), raveling and bleed strip range from acceptable (0) to highly deficient (5), guardrail, shoulder, alignment and lane width deficiencies ranged from none (0) to very high (4).

3.2. Safety performance modeling

Six safety performance models were developed for Tanzania depending on land use and potential for improvement. Land use was divided into urban and rural. According to

Deficiency	0	1	2	3	4	5
Roughness[1]	0	279	2034	5214	1131	N/A
Rutting	3069	3927	1155	N/A	N/A	N/A
Raveling	4182	1929	696	918	282	144
Bleed strip	6390	327	96	558	114	666
Guard rail	8256	234	117	51	N/A	N/A
Improve Shoulder	6	252	4026	4374	N/A	N/A
New Shoulder	5787	2559	312	N/A	N/A	
Alignment	3486	1404	567	3201	N/A	N/A
Lane Width	732	180	6852	891	N/A	N/A

Note: [1]very good IRI < 1.5; good IRI from 1.5 to 2; fair from 2 to 3; poor from 3 to 5 and very poor > 5

Fig. 1. Tanzania Road Network and Inventory of deficiencies (segment counts)

the *World Bank* (2011), economic development of Tanzania reached 6% of GDP growth in 2009 and, population growth for the same year near to 3%. Both amounts were assumed to correlate to rural and urban development, and to traffic growth. Thereafter max traffic capacity per lane was based on 1800 vehicles per lane per hour. The lifespan of any segment, for safety performance, was limited by such level of service and derived from the traditional equation of compound growth.

Likelihood (Eq (1)) was based on six contributing factors as follows: pavement surface from roughness, skid resistance from raveling and bleeding records, adequate coverage of guardrail from length of horizontal and vertical curves combined with roadside grades, shoulder adequacy (width and surface), lane width compliance (standard width from 3.5 m to 3.7 m) and intensity of curves (vertical and horizontal). Specific safety improvements were established for each of those factors as shown on Table 1. No data was available for other elements (i.e., pavement marking, traffic signs and etc.). However, it is recognized that such elements should be included in future updates of the model when sufficient information becomes available.

4. Results and discussion

A first analysis was conducted to identify required levels of budget to achieve optimal values of safety and condition (Fig. 2). This budget fluctuated from zero to 28 mln EUR, and with an average of 8.5 mln EUR per year to achieve optimal levels of service (Scenario G). With such a budget it was possible to achieve and sustain optimal values of both condition and safety indexes, while minimizing expenditure (Scenario G, Figs 2 and 3). The analysis proceeded by running a series of scenarios based on variable levels of budget aimed to minimize safety issues and maximize condition. It was found that good results could be achieved with as little as 5 mln EUR (Scenarios A to F).

A weighted global objective (Eq (2)) was used to combine condition and safety. Variable weights α and β were used to establish six scenarios intended to determine the ideal solution. A two stage analysis followed; first by determining dominance criteria for every scenario, during a 15 year period of analysis and fixed budget of 5 mln EUR and, secondly, by looking at the performance criteria of each non inferior solution. Scenarios C, D and E were dropped off the analysis, because they were inferior and dominated by scenario B (Table 3).

Plots of performance (mean levels of network safety and condition) across time were used to determine the goodness of each solution in terms achievement and sustainment of acceptable results (Fig. 3). Alternatives A and F were discarded after analyzing their performance and realizing that they produced solutions that achieved better values of one objective in detriment of the other one (Fig. 3).

It was confirmed that, as suggested in the literature (Haas *et al.* 1994), applying a silo approach (1 mln for safety and 7 mln for condition) based on alternative B

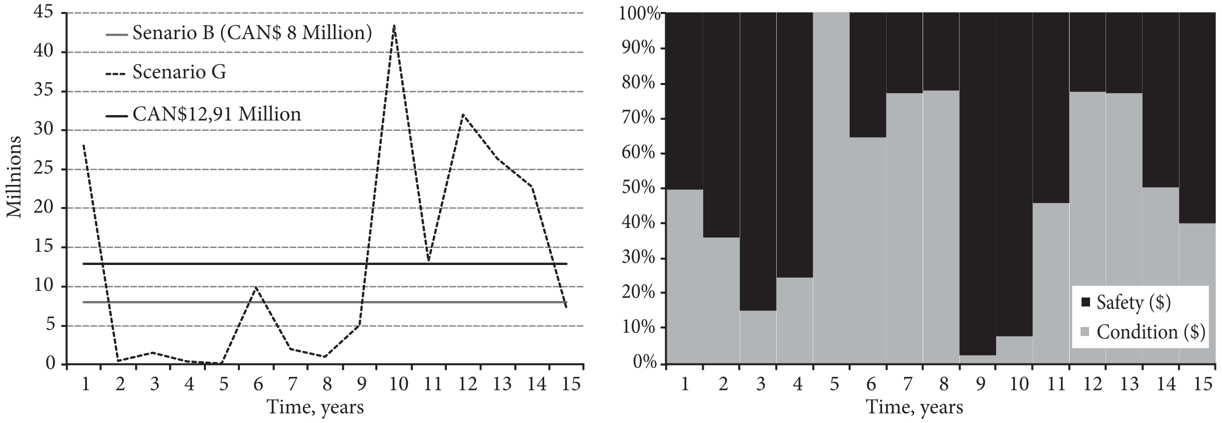

Fig. 2. Mean annual expenditure and budget allocation for Scenario B

Table 3. Dominance and performance criteria for a fixed budget of 5 mln EUR

Scenario	Objective 1 (α)	Objective 2 (β)	Maximize	Minimize	Dominance criteria	Performace criteria
			Pavement Condition	Safety Index		
A	0.9	0.1	361.4E+07	2.2E+07	Non Inferior	PCI dominated
B	0.7	0.3	357.2E+07	2.0E+07	Non Inferior	Final Solution
C	0.5	0.5	356.1E+07	2.0E+07	Dominated by B	
D	0.4	0.6	355.3E+07	2.0E+07	Dominated by B	
E	0.3	0.7	351.4E+07	2.0E+07	Dominated by B	
F	0.1	0.9	325.8E+07	1.9E+07	Non Inferior	SI Dominated

Note: Scenario G is not included because it has a variable budget.

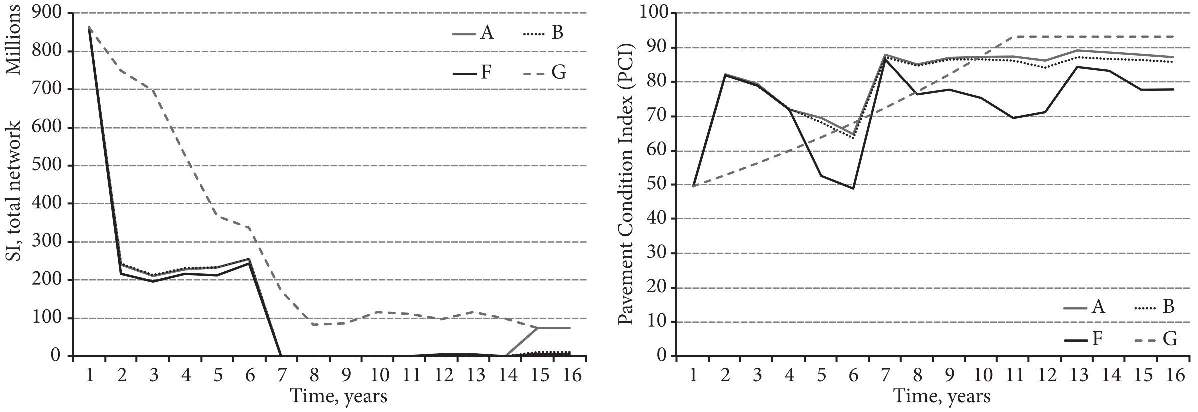

Fig. 3. Mean network condition and progression of safety deficient roads

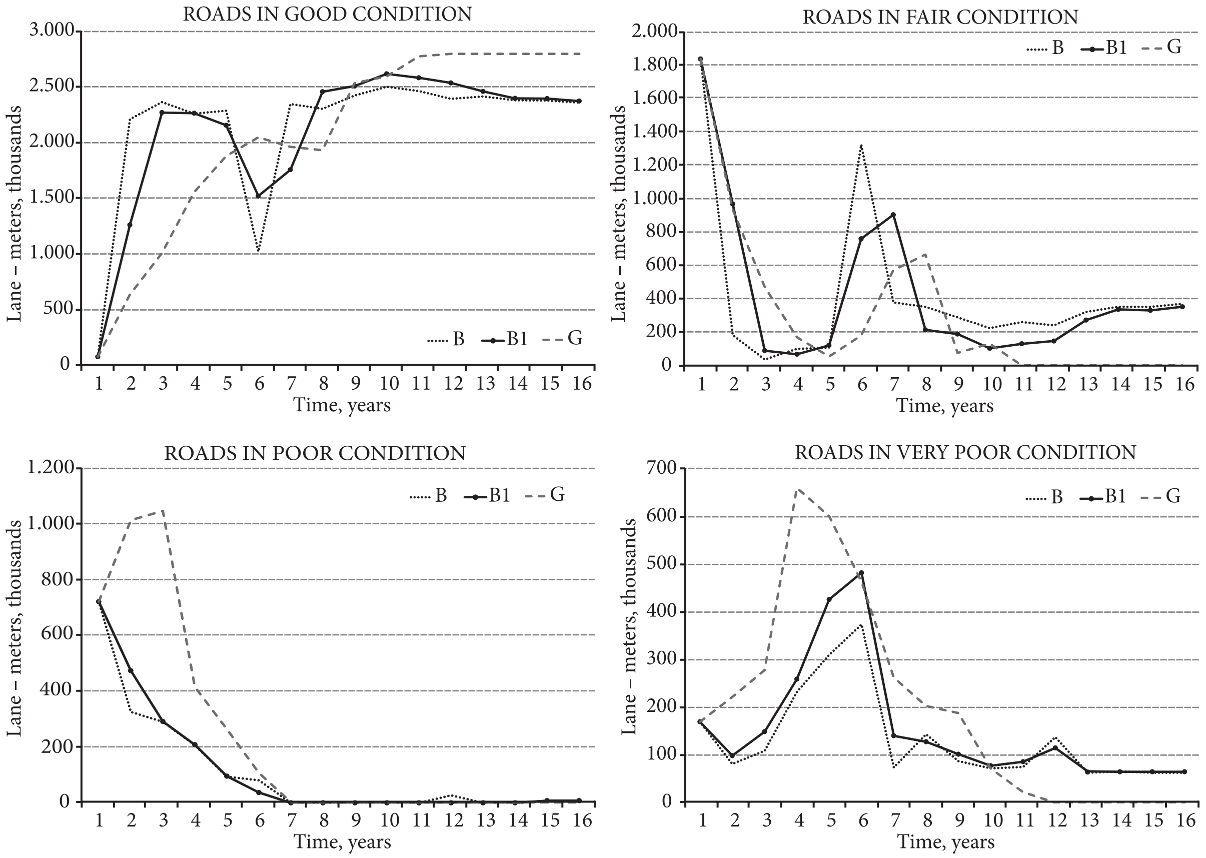

Fig. 4. Qualitative progression of road condition

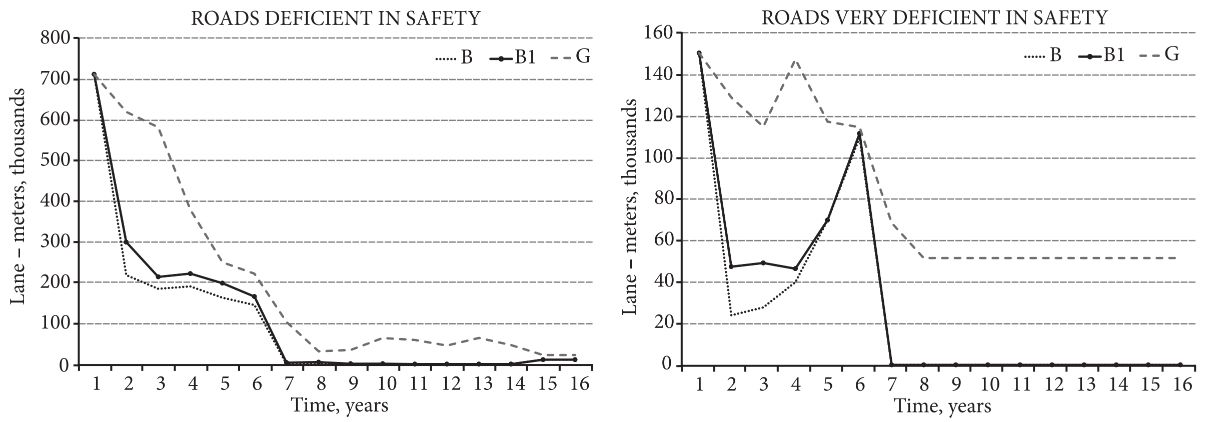

Fig. 5. Qualitative progression of road safety

(Scenario B1) worsen the results by producing a shift that delayed the recovery rate of both safety and condition (Figs 4 and 5). Such a delay signifies higher social cost in the form of avoidable collisions and safety issues (property damage, fatalities and injuries), economic losses (vehicle operating cost, passenger hours) and regional productivity drop in competitiveness from deferred maintenance and rehabilitation.

Table 4. Investments allocation with 5 mln EUR – Scenario B (in thousands of EUR)

Period	Shoulder improvement	New shoulder	Mill and overlay	Micro surface for safety	Safety minor	Safety major	Crack sealing	Micro surface for condition	Minor rehabilitation	Major rehab	Second seal
1	1.921	2.117	0	0	0	0	0	3.269	679	0	14
2	71	3.563	29	1.463	0	0	0	1.690	1.025	0	158
3	23	1.040	68	5.663	0	0	156	157	210	241	441
4	95	142	134	5.666	0	0	186	107	0	645	1.024
5	3	0	0	0	0	0	9	7.077	0	0	910
6	0	0	0	0	1.629	242	14	5.137	0	0	0
7	0	0	0	0	1.843	0	175	5.981	0	0	0
8	0	0	0	0	1.780	0	46	6.174	0	0	0
9	0	0	0	0	1.941	0	10	182	0	0	0
10	0	0	0	0	1.870	0	17	607	0	0	0
11	0	0	0	0	1.882	0	191	3.467	0	0	0
12	30	0	0	0	1.780	0	0	6.190	0	0	0
13	0	0	0	0	1.843	0	7	6.150	0	0	0
14	38	0	0	0	1.812	0	0	4.013	0	0	0
15	0	0	0	0	1.885	0	0	3194	0	0	0

Table 5. Investment allocation 8.5 mln EUR – Scenario B (in thousands of EUR)

Period	Realignment	Shoulder Improvement	New Shoulder	Mill and overlay	Micro surface for Safety	Safety minor	Safety Major	Crack sealing	Micro surface for Condition	Minor Rehabilitation	Major Rehab	Second Seal
1	0	1.975	5.104	0	600	0	0	0	2.495	1.953	600	182
2	4.025	53	820	149	5.225	0	0	0	717	1.669	0	250
3	10.977	24	714	76	315	0	0	0	157	210	0	436
4	247	88	223	0	6.355	0	0	4	4.924	215	0	853
5	0	0	0	0	0	0	0	0	12.144	0	0	766
6	0	0	0	0	0	1.629	213	0	10.390	0	0	0
7	0	0	0	0	0	1.823	0	0	11.087	0	0	0
8	0	0	0	0	0	1.774	0	22	11.055	0	0	0
9	0	4	0	0	0	1.909	0	0	5.837	0	0	0
10	0	0	0	0	0	1.773	0	0	11.137	0	0	0
11	0	0	0	0	0	1.826	0	0	10.847	0	0	0
12	0	13	0	0	0	1.773	7	0	11.117	0	0	0
13	0	0	0	0	0	1.829	17	0	11.063	0	0	0
14	0	23	0	0	0	1.911	0	0	3.238	0	0	0
15	0	0	0	0	0	2.004	0	0	0	0	0	0

It was found that the approach of maximizing condition and minimizing safety by means of a global objective with relative weights of 0.7 and 0.3 for condition and safety (correspondingly) produced almost as good results as the optimization with variable levels of budget (Scenario G), but with a much lower and stable budget requirement (38% less). It was noticed that, for all scenarios, the amount of roads with safety issues, reached similar levels towards year 5. This can be explained by corrections of safety issues for the known portion of the network finalizing at that time. New deficiencies detected by future safety audits motivated the provision of generic treatments. Safety levels for current segments were increased annually by correlating it with expected traffic growth.

According to Fig. 5, scenario B represented a more balanced solution by allocating treatments for improving road condition and reducing safety issues during the analysis period. It also required lower and certain (stable) levels of budget. Tables 4 and 5 show the allocation of resources to both objectives of Scenario B (two levels of budget). For the 5 mln EUR budget, it was observed that the system focused more on applying individual treatments than realigning roads. Surface treatments received the majority of funding allocated for road safety and condition combined, followed by some investments in shoulders. An increase in budget to 8.5 mln EUR, for the same scenario (B), resulted in a very similar allocation of resources (Table 5). Minor differences were investments towards correcting geometric deficiencies in years two and three, resulting in combined safety and condition improvements. Disregarding levels of funding, resources were used in years 1 to 5 to stabilize safety and condition, thereafter investing on preserving both objectives at acceptable levels. However, this observation contradicts future needs on capital upgrades to correct inadequacy of crossings and intersections once traffic volumes have surpassed certain thresholds, for which a deeper understanding of deficiencies from road audits is required.

This first allocation of investments was used for a strategic analysis, a coordination of treatments for safety and condition will be required to prepare tactical and operational plans. Detailed knowledge of all safety issues (pavement marking, traffic signs, etc) will be required for coordinating. In service road safety audits should be conducted for the entire network in order to better typify safety deficiencies in order to refine this first cut model.

5. Conclusions

This paper has illustrated the initial development of a network level lifecycle-optimization for road safety and pavement condition. The proposed model develops safety performance models based on land use and severity of safety issues. Ability to predict long term road safety deficiencies was limited to site-specific characteristics which can only be learnt from safety audits. Therefore, safety deficiencies were split into known and unknown. Known safety issues were corrected in about five years. Traffic growth was used from that point in time to reflect the increase in unknown safety related issues and, generic safety corrective actions, at three different levels (surface corrections, new hardware and realignment), were incorporated in the analysis to consider investment needs for a longer term budget exercise. In practice, tactical and operational planning will require in service safety audits to identify deficiencies in order to prepare future tactical plans. Traditional Pareto optimality analysis, complemented by ensuring good performance across time of road safety and pavement condition, was used to identify recommended weights to combine both objectives into a global indicator for the integer programming optimization. It was found that traditional practices for achieving and sustaining good levels of service would have demanded a mean annual budget of almost 9 mln EUR, with large variations on budget requirements (base case), meanwhile a maximization scenario with a fixed budget of 5 mln EUR, for a weighted objective (0.3 and 0.7 for condition and safety, correspondingly), resulted in almost as good results as the base case but, in average with 38% less budget. It was observed that known safety deficiencies got corrected during the first 5 years, disregarding level of funding. The majority of the investments were allocated in surface-related treatments that helped improve both: condition and safety (i.e., micro surfacing). When more resources were available, large investments for correcting geometric issues were observed in years two and three which translated into joint safety and condition improvements. Results from this paper should be understood within the aim to have a first cut model, capable of providing guidance in budget requirements and of preparing a first tactical plan. It presents the opportunity to prioritize investments for improving road safety and pavement condition with a good degree of certainty in the short term, in the understanding that these results must be complemented and updated after conducting road safety audits on the entire network to better identify safety deficiencies at specific sites. In such a case, a more reasonable allocation of resources will result after allocating treatments to correct safety deficiencies related to exposure, severity and likelihood. For a low income nation as Tanzania, this first model signifies the possibility to align its management framework to be compliant with United Nations call on reducing fatalities during the 2011–2020 decade.

References

Anastasopoulos, P.; Mannering, F. 2009. A Note on Modeling Vehicle Accident Frequencies with Random-Parameters Count Models, *Accident Analysis and Prevention* 41(1): 153–159. http://dx.doi.org/10.1016/j.aap.2008.10.005

De Leur, P.; Sayed, T. 2002. Development of a Road Safety Risk Index, *Transportation Research Record* 1784: 33–42. http://dx.doi.org/10.3141/1784-05

El-Basyouny, K.; Sayed, T. 2010. Safety Performance Functions with Measurement Errors in Traffic Volume, *Safety Science* 48(10): 1339–1344. http://dx.doi.org/10.1016/j.ssci.2010.05.005

Haas, R.; Hudson, W. R.; Zaniewski, J. 1994. *Modern Pavement Management*. Malabar, FL: Krieger Publishing Company. 604 p.

Hauer, E. 1997. *Observational before-after Studies in Road Safety*. New York: Elsevier Science Inc. 306 p.

Feunekes, U.; Palmer, S.; Feunekes, A.; MacNaughton, J.; Cunningham, J.; Mathisen, K. 2011. Taking the Politics Out of Paving: Achieving Transportation Asset Management Excellence through OR, *Interfaces* 41(1): 51–65. http://dx.doi.org/10.1287/inte.1100.0520

FHWA. 2009. HERS-ST: Highway Economic Requirement System – State Version. Users Guide. Federal Highway Administration. Washington, DC. [Cited October 18th 2012]. Available from Internet: http://www.fhwa.dot.gov/asset/hersst/pubs/users/users_guide09.pdf

Koptis, E.; Cropper, M. 2005. Traffic Fatalities and Economic Growth, *Accident Analysis and Prevention* 37(1): 169–178. http://dx.doi.org/10.1016/j.aap.2004.04.006

Li, Z.; Madanu, S. 2008. *A Methodology for Integrating Road Safety Hardware Management into the Overall Highway Asset Management Program*. Report MRUTC 08-06. Dept of Transportation. Washington, DC.

Lytton, R. 1994. Optimization Techniques, in *Proc. of the 3rd International Conference on Managing Pavements*. San Antonio, Texas. 16–42.

Mumford, J. 2011. Road Deaths in Developing Countries, the Challenge of Dysfunctional Roads, in *Proc. of the 14th Road Safety on Four Continents*. 14–16 November, 2007, Bangkok, Thailand.

Odgen, K. W. 1996. *Safer Roads: a Guide to Road Safety Engineering*. London: Avebury Technical. 536 p.

Ong, G. P.; Fwa, T. F. 2007. Prediction of Wet-Pavement Skid Resistance and Hydroplaning Potential, *Transportation Research Record* 2005: 160–171. http://dx.doi.org/10.3141/2005-17

Paterson, W. D. O.; Attoh-Okine, B. 1992. Summary of Models of Pavement Road Deterioration Based on HDM-III, *Transportation Research Record* 1344: 99–105.

Road Safety Manual. 2003. 2nd edition. Worl Road Asociacion PIARC. R2utemarket. 602 p.

Revelle, C. S.; Whitlatch, E.; Wright J. 2003. *Civil and Environmental Systems Engineering*. 2nd edition. New Jersey: Prentice Hall. 552 p.

Tighe, S.; Li, N.; Falls, L. C.; Haas, R. 2001. Incorporating Road Safety into Pavement Management, *Transportation Research Record* 1699: 1–10. http://dx.doi.org/10.3141/1699-01

Watanatada *et al*. 1987. The Highway Design and Maintenance Standard Model. Vol. 1. The World Bank. Washington, DC. The John Hopkins University Press.

World Bank. 2011. World Development Indicators. The International Bank for Reconstruction and Development (The World Bank). Washington DC. [Available from internet]: http://data.worldbank.org/data-catalog/world-development-indicators

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