Comprehensive Pavement Management with Network Effect: Practical Application to Ugandan Pavement Network

(ネットワーク効果を備えた包括的な舗装管理：ウガンダ舗装ネットワークへの実用的なアプリケーション)

Felix OBUNGUTA[1] and Kakuya MATSUSHIMA[2]
[1]Graduate student and [2]Associate Professor, Kyoto University, Graduate School of Engineering, Department of Urban Management,
Katsura Campus Nishikyo-ku, Kyoto, Japan, 615-8540;
E-mail[1]: obunguta.felix.68w@st.kyoto-u.ac.jp/obongutafelix@gmail.com
E-mail[2]: matsushima.kakuya.7u@kyoto-u.ac.jp

Abstract: Pavement management has always proved a challenge to policy makers since management has been fragmented with inadequacies in road capacity (congestion) handled by planners and structural failure by engineers yet these aspects are intertwined. This study attempts to solve this problem by developing a comprehensive pavement management model combining both capacity and structural aspects. Pavement management actions (repair, upgrade and capacity improvements) which reduce travel time were handled comprehensively in the model. There have been similar attempts in the past but the novelty of this study lies in its comprehensiveness and practicality. The optimum interventions on a road section were determined by minimizing total social cost. Social cost is defined as a summation of user cost (travel time cost) and road construction and maintenance cost (road agency cost). To test the applicability of the model, an empirical study was carried out on Ugandan national roads.

Key words: *Comprehensive pavement management, travel time reduction, social cost optimization*

1. INTRODUCTION

(1) Pavement management

Pavement management policy may be crafted to deal with the inadequacies in road capacity and durability leading to congestion and structural failure respectively. Previously planners dealt with only congestion leaving pavement failure to engineers. As a result, pavement intervention did not always fully meet required maintenance and improvement needs. Furthermore, with the current problem of rapidly aging infrastructure in a number of countries such as the USA, the gap between maintenance needs and finance allocation is widening (Small et al. 1989, Small and Winston 1988). Maintenance finance is normally obtained through road tolls, taxes, vehicle registration and inspection fees, parking fees, other government allocation and grants amidst growing opposition by road users against charges yet they demand high quality road service. Road users claim road damage is due to poor designs and weather conditions skipping traffic loading as a major damage cause. This drove governments into introducing indirect taxes especially on fuel. This too is likely to become insufficient especially given ongoing technology improvements. More fuel-efficient cars are being introduced and electric cars are increasing their usership share. A holistic approach is thus needed to develop efficient pavement management policy encompassing both capacity and structural strength aspects cost effectively (Small et al. 1989 and Newbery 1989).

A number of studies have attempted to solve challenges associated with pavement network management. Efficient road utilization can be achieved by policies involving charging road users to use the road service (road tolls) or the road agency (government) shouldering the development and maintenance cost obtained from other sources such as "non-road" taxes. The former policies treat road service as a business while the latter is popular considering road politics. Both policies may generate efficient road use based on existing conditions. A study by Podgorski and Kockelman (2006) showed that about 70% of respondents in Texas, USA agreed on keeping existing roads toll-free and first attending to them. This highlighted the general perceived opposition by majority road users against toll charges.

Verhoef and Small (2004), Small and Yan (2001) investigated road pricing considering differentiated products to maximize benefits of tolling different from earlier studies that considered homogeneous users. These studies demonstrated the importance of heterogeneity in value of time under congested conditions considering different tolling regimes.

Small and Winston (1988) determined optimal highway durability defined by pavement thickness[1] considering heterogeneous users and presented dramatic findings for the trucking industry that is characterized by high equivalent single-axle loads (ESALs). Their results supported the growing consensus that heavy vehicles impose very high marginal pavement-wear costs on many existing roads.

Studies by Newbery (1988, 1989) and Small et al. (1989) investigated specific road cost recovery considering road damage costs and congestion costs. They investigated whether congestion and durability charges recovered costs due to road damage attributed to vehicle loading (especially by trucks) and weather, congestion and other non-traffic related costs such as policing and lighting.

Liu and Wang (2016) used the Stochastic User Equilibrium (SUE) approach based on the Logit model to determine appropriate extensions to road networks by minimizing total network travel time. On the other hand, Lin and Lin (2011) develop a pavement maintenance strategy for Kaohsiung, Taiwan by using pavement roughness data (IRI) and traffic volume as the main criteria to support the decision process on pavement

---

[1] Small and Winston (1988) concede that pavement durability may be defined in other ways including better materials, drainage and construction techniques. Later on in this study, pavement durability was defined in terms of pavement condition measured using a roughness index.

maintenance prioritization in addition to consulting experts.

In reality, political decisions normally overshadow technical plans. Therefore this study develops optimal road network management considering toll-free conditions. The rest of the article is organized as follows; the study scope and objectives are states at the end of Section 1, Section 2 presents the model, Section 3 describes the empirical study and Section 4 concludes the article.

(2) Study scope and objectives

Road networks are made up of origins (O) and destinations (D) joined by links that comprise of sections and nodes. Nodes are often seen as junctions or points representing change in link characteristics e.g. travel speed, capacity etc. (Luis, 2008).

This study investigates how road intervention actions (repair, upgrade and capacity improvements) on sections reduce total social cost i.e. user cost (travel time cost) and road construction and maintenance cost (road agency cost). At the micro level, road users seek to minimize individual travel cost while at the macro level, the goal is to minimize total social cost. In light of this, the objectives of this study are;

1) To develop a comprehensive pavement management model.
2) To determine appropriate pavement interventions that minimize social cost.
3) To test the applicability of the model through an empirical study on an actual road network.

2. MODEL

(1) Model framework

Consider a road network with sections $k(k=1,\ldots,K)$. Each road section k is of pavement type, ρ^k, pavement condition, i^k and requires travel time, τ^k to traverse. Pavement type could be set according to paved or unpaved and flexible or rigid pavements. Travel time on a section is a function of pavement condition and type, traffic volume (v^k) and section capacity (c^k). Travel time was calculated using the modified Bureau of Public Roads (BPR) power function (BPR, 1964).

Pavement failure may be caused by traffic loading, moisture penetration to sub layers and significant temperature variations (i.e. loading and weather). These factors affecting pavement durability were captured in pavement condition. Traffic volume on roads is one of the major indicators of the level of service of the road network. Inadequacy in road capacity was included in the model by considering the volume: capacity (v^k/c^k) ratio on a road section.

This study examines a no-toll regime (NT) (Small and Yan, 2001) that is mainly influenced by political, user resistance to pay tolls and other considerations. In such a case, road users may face travel time costs and vehicle operation costs (VOCs) while the road agency bears road construction and maintenance costs. Homogeneous road users were considered so VOCs may be uniform hence considering travel time costs as user costs was sufficient. Also since the NT regime was considered, v^k may be assumed to remain constant on each section k. Optimum policies can be obtained by minimizing social costs (user and agency costs).

Travel time reduction can be achieved by making improvements on a section (upgrade type, increase capacity and condition improvement) (Figure 1). Interventions that minimize social cost, ξ, form an optimum policy.

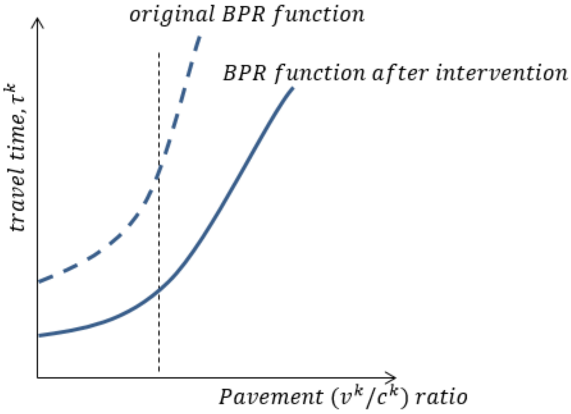

Figure 1 BPR function before and after intervention

(2) Social cost optimization

Social cost is defined as a summation of road user and agency costs. Road users face a travel time cost while the road agency bears road construction and maintenance cost.

Travel time, $\tau^k(i^k,\rho^k,v^k,c^k)$, is determined as a function of pavement condition, i^k, pavement type, ρ^k, traffic volume, v^k and section capacity, c^k as shown in the modified BPR function[2].

$$\tau^k=\tau^{k,0}\left[1+\zeta\left\{1+\sum_{i^k=1}^{J}\left(\alpha_{i^k}g^{i^k}\right)+\alpha_{J+1}\rho^k\right\}\left(\frac{v^k}{c^k}\right)^n\right] \quad (1)$$

$$\rho^k=\begin{cases}0 & if\ \ k\ is\ \ paved\\ 1 & if\ k\ is\ unpaved\end{cases}$$

$$g^{i^k}=\begin{cases}i^k & if\ \ k\ is\ in\ condition\ i^k\\ 0 & otherwise\end{cases}$$
$$(i^k=1,\ldots,J)$$

Where;
$\alpha_{i^k},\alpha_{J+1},\zeta$ and n are unknown parameters
$\tau^{k,0}$ is free flow travel time
J is the terminal condition state of a pavement section
ρ^k and g^{i^k} are dummy variables for pavement type and condition respectively

Free Flow Speed (FFS) is the speed achieved by a single vehicle when there are no other vehicles on a corridor (road section). It follows that free flow travel time is the time taken to travel the full length of road section at FFS. During free flow, $\zeta=0$. Capacity is the flow that produces the minimum acceptable journey speed. At full capacity $(v^k=c^k)$, critical speed is reached. At critical speed operations are unstable and any slight

---

[2] The original BPR function has power $n=4$ and $\zeta=0.15$ and does not include the condition and pavement type term.

disturbance to the network causes traffic flow breakdown (FHWA, 2018).

Road users may prefer a specific section leading to negative impacts e.g. congestion, pollution etc. Oversized vehicles and junctions (in urban settings) are the main contributors to congestion (Lu et al, 2016 and Luis, 2008). In this study, these externalities were not directly considered save for congestion that is captured in the terms of equation (1) which include the volume capacity ratio (delay cost).

Pavement management decisions such as improving condition, increasing capacity, upgrading roads and no action are under taken by the road agency. Action A_i is taken to improve section condition, action A_c to increase section capacity, action A_u to upgrade roads and action A_0 in case no action is taken. This attracts an intervention unit cost, $C^{k,A}$, considering specified intervention action $A(A = A_i, A_c, A_u, A_0)$ and section area, a_k improved ($C^{k,A_0} = 0$). When intervention occurs;

$$i^k = \begin{cases} 0 & if\ A_i \\ i^k & otherwise\ \ A_0 \end{cases} \tag{2}$$

$$c^k = \begin{cases} mc^k & if\ \ A_c \\ c^k & otherwise\ \ A_0 \end{cases} \tag{3}$$

$$\rho^k = \begin{cases} 0 & if\ \ A_u \\ 1 & otherwise\ \ A_0 \end{cases} \tag{4}$$

Where;

m is the percentage change in capacity

Actions A_i, A_c, A_u and A_0 are performed to minimize social cost, $\xi(v^k, \tau^k, C^{k,A})$, defined as[3];

$$\xi = \sum_{k=1}^{K}\left\{(365 * v^k \omega \tau^{k,A}) + \sum_{A} a_k C^{k,A}\right\} \tag{5}$$

And the objective function;

$$\min_{A}\ \xi \tag{6}$$

$$Subject\ to$$

$$A \in \Gamma \tag{7}$$

$$\sum_{k=1}^{K}\sum_{A} a_k C^{k,A} \in \Omega \tag{8}$$

Where;

Γ is a set of all feasible actions

Ω is the budget limit

ω is the monetary value of one unit of travel time

v^k is Average Annual Daily Traffic (AADT) on a section

$\tau^{k,A}$ is the new travel time on a section after intervention, A

3. EMPIRICAL STUDY

(1) Introduction

In this section, an empirical study was carried out on Ugandan national roads managed by Uganda National Roads Authority (UNRA). First, a data summary of the Uganda national roads data base was presented and road interventions inferred by the data were identified. The database had data from 2009 to 2019. Data from 2009 to 2016 was disjointed and data in 2019 was partial. Complete data for 2017 and 2018 consisting of traffic, average speed, inventory and condition data was selected for the empirical study.

The entire data sample was used to calibrate the modified BPR equation. To test the model, one OD pair along the Northern Corridor route in East Africa was selected. The Northern Corridor is a route originating from Mombasa port in Kenya extending to the hinterland (i.e. Uganda, Rwanda, South Sudan and Eastern Congo) (Figure 2). Considering a budget level, optimum section interventions that minimised the total social cost for the selected OD pair were determined.

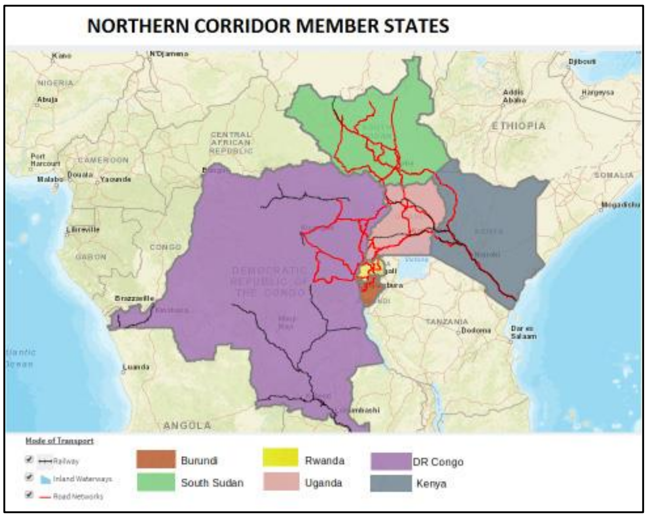

Figure 2 Northern Corridor route in East Africa (Source: Northern Corridor Transit and Transport Coordination Authority, 2020)

(2) Data summary

Road sections in the Ugandan national roads database were 1km long. Pavement condition was measured in form of International Roughness Index (IRI) in mm/m per section and traffic volume in terms of Average Annual Daily Traffic (AADT) per road section.

Pavement condition was categorised into condition states $i^k (i^k = 1,2,3,4)$ based on IRI severity for paved and unpaved roads (Table 1).

Table 1: Categorization of condition measured in IRI (mm/m) (MoWT, 2011-17)

Categorisation	1.Good	2.Fair	3.Poor	4.Bad
Paved	0-3.50	3.51-5.00	5.01-6.50	>6.50
Unpaved	0-6.00	6.01-8.00	8.01-9.50	>9.50

---

[3] It was assumed that repair action is done once in a year on a road section and so the user cost was computed for 365 days.

Table 2 shows the categorization of road sections by type in 2017 and 2018. It was revealed that 199 sections where upgraded from Gravel (G) in 2017 to Asphalt Concrete (AC) in 2018.

Table 2: Sections type per year

Year	Pavement type						Total (Out of 2624)
	Paved (Pv)				Unpaved (UPv)		
	Flexible			Rigid	Gravel (G)	Earth (E)	
	*AC	*PB	*SD	*CC			
2017	890		1511	24	42		2467
2018	1089		1511	24			2624

**Asphalt Concrete (AC), Surface dressed (SD), Permeable Base (PB), Cement Concrete (CC)*

It was further shown that 1556 sections had no change in condition, 456 sections deteriorated in condition and 413 sections showed improved condition suggesting that they were repaired between 2017 and 2018 (Table 3).

Table 3: Number of sections showing change in condition between 2017 and 2018

		2018			
	Condition	1.Good	2.Fair	3.Poor	4.Bad
2017	1.Good	996	217	53	18
	2.Fair	353	514	127	26
	3.Poor	17	55	44	15
	4.Bad	1	3	2	2

Note: Along major diagonal shows no change in condition, above major diagonal shows deterioration and below major diagonal shows improvement in condition (Upgraded sections excluded).

Inventory data on pavement width revealed that 37 sections had capacity improvement from 1 to 2 lanes (Table 4). These sections had increase in capacity during their upgrade from unpaved to paved standard between 2017 and 2018.

Table 4: Capacity of road sections in 2018

Width (w) range (m)	No. of lanes (ln)	Capacity (PCU/ln/h)*	No. of sections		
			2017		2018
			Pv	UPv	Pv
$3 < w \leq 5$	1	2200		37	
$w > 5$	2	4400	2425	162	2624

**Capacity from US Highway Capacity Manual (US-HCM) 2000 (TRB, 2000)*

Table 5 shows section volume: capacity (v^k/c^k) ratio. In 2017, 6.7% of the surveyed sections were congested while in 2018, 3.1% of the surveyed sections were congested ($(v^k/c^k) > 1$). The reduction in percentage of congested sections was attributable to increased surveys and traffic fluctuation on the network.

Table 5: Section Volume: capacity ratio

Year	No. of sections		
	$(v^k/c^k) < 0.5$	$0.5 < (v^k/c^k) < 1$	$(v^k/c^k) > 1$
2017	2126	175	166
2018	2281	261	82

The major points to note from data summary were;

1) 199 unpaved sections where upgraded to paved between 2017 and 2018. Of these, 37 unpaved sections had capacity improvement from 1 to 2 lanes.
2) 413 sections were improved between 2017 and 2018.
3) 6.7% and 3.1% of surveyed sections were congested in 2017 and 2018 respectively.

(3) Calibration of the modified BPR equation

Generally the FFS on Ugandan national roads, needed to obtain free flow travel time, can be approximated to 80km/h as shown in Figure 3. Traffic volume was converted to similar units i.e. Passenger Car Units (PCU) according to Table 6.

In the calibration of the modified BPR equation, the following considerations were made;

1) $n = 4$ (fixed as in original BPR equation)
2) In conversion of vehicles into PCUs, rolling terrain (common in Uganda) was adopted.
3) Since section capacity was measured in PCU/lane/hour, the daily traffic volume was multiplied by the 30th Hourly Volume (HV) during year factor ($K_{30^{th}} = 0.15$) (MoWT, 2010) to convert it to hourly volume.

In the calibration, the objective function was defined as a minimization of the sum of squared deviations between predicted travel time and actual measured travel time on all road sections[4].

$$\min_{\substack{\alpha_{i^k}, \alpha_{J+1}, \zeta \\ (i^k = 1, \dots, J)}} \sum_{k=1}^{K} \left(\tau^k_{model} - \tau^k_{measured}\right)^2 \tag{9}$$

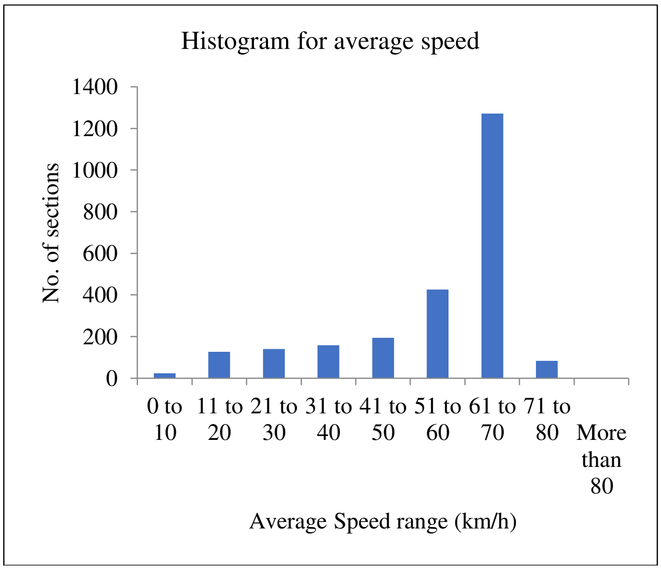

Figure 3 Histogram for average speed on surveyed Ugandan national road sections

---

[4] The estimated travel time on Ugandan roads had a lot of noise owing to the fact that travel time is also affected by road geometry and driver behavior but not only road condition, traffic volume and pavement type as considered in this study hence sections with unrealistic travel time were excluded.

Table 6: PCU factors adopted from MoWT (2010) and FHWA (2014)

Vehicle type	Terrain		
	Level	Rolling	Mountainous
Motorcycles and scooters	1.0	1.0	1.5
Saloon cars and taxis	1.0	1.0	1.5
Light Goods	1.0	1.5	3.0
Small Buses	1.0	1.5	3.0
Medium Buses	2.0	4.0	6.0
Large Buses	2.0	4.0	6.0
Light Trucks	1.0	1.5	3.0
Medium Trucks	2.5	5.0	10.0
Truck trailer/ semi-trailer	3.5	8.0	20.0
Bicycles	0.5	0.5	NA*
Carts	1.0	1.0	NA

Parameters $(\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \zeta)$ are estimated as shown in Table 7 using the entire data sample (4,368 sections in 2017 and 2018). Considering a 95% confidence interval [-1.96, 1.96], a $z-value$ of -199.23 was obtained showing that the model imperfectly predicts the expected travel time due to the noise in the data noted earlier. Figure 4 shows a plot of estimated travel time against measured travel time on surveyed Ugandan roads. It can be seen that the model predicted travel time on a number of sections approximately equal to the free flow travel time because the national road network was not in fully congested conditions.

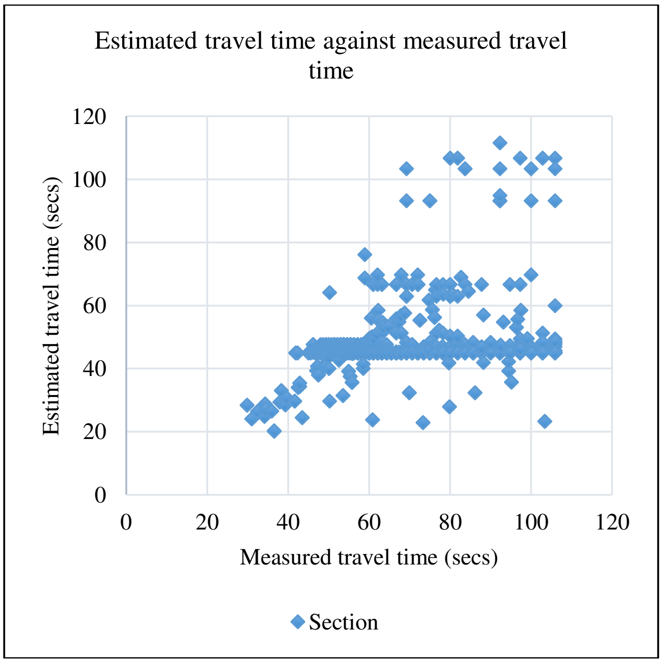

Figure 4 Estimated travel time vs. measured travel time on surveyed Ugandan national roads

Table 7: Solution for constants in modified BPR equation

Constant	Estimated value
α_1	3.2194
α_2	2.0505
α_3	1.6067
α_4	1.9880
α_5	3.0000
ζ	0.0085
$\tau^k_{measured}$ mean	61.1 (11.99)*
τ^k_{model} mean	45.5 (5.18)*
$z-$value	-199.23

* τ^k *was measured in seconds and the value is parentheses is the standard deviation for a sample size of 4,368 sections in 2017 and 2018.*

(4) Did interventions reduce travel time on surveyed Ugandan roads?

In this subsection, an investigation was carried out whether performed intervention actions on surveyed Uganda national road sections achieved travel cost (time) reduction. Based on the revelations of the data summary, interventions actions performed between 2017 and 2018 were;

1) 37 sections with both capacity increase and upgrade
2) 162 sections with only upgrade
3) 431 sections with only condition improvement

It can be deduced that;

1) Condition improvement achieved significant travel time reduction on sections whose volume: capacity ratio was greater than 1 (congested sections) (Figure 5).
2) Also upgrade alone did not achieve travel time reduction on sections with a low volume: capacity ratio (Figure 6).
3) Upgrade and capacity increase did not achieve travel time reduction for sections with a low volume: capacity ratio (Figure 7).

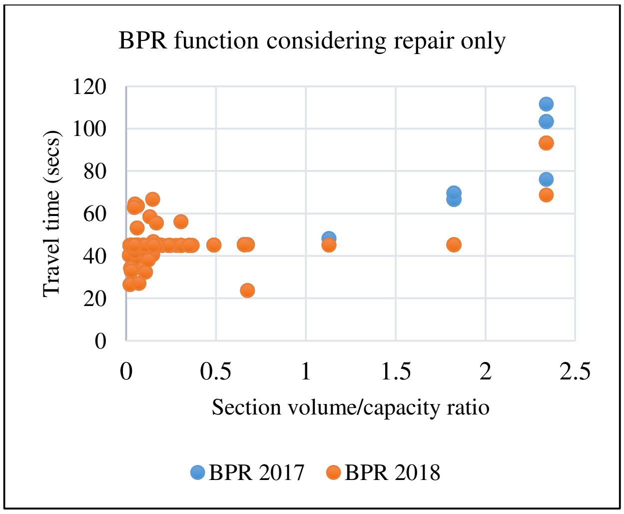

Figure 5 Change in travel time on Ugandan national roads considering condition improvement only for 431 sections

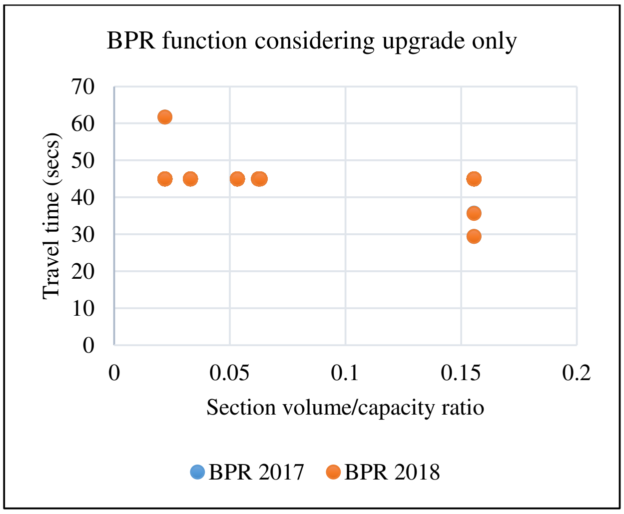

Figure 6 Change in travel time on Ugandan national roads considering upgrade only for 162 sections

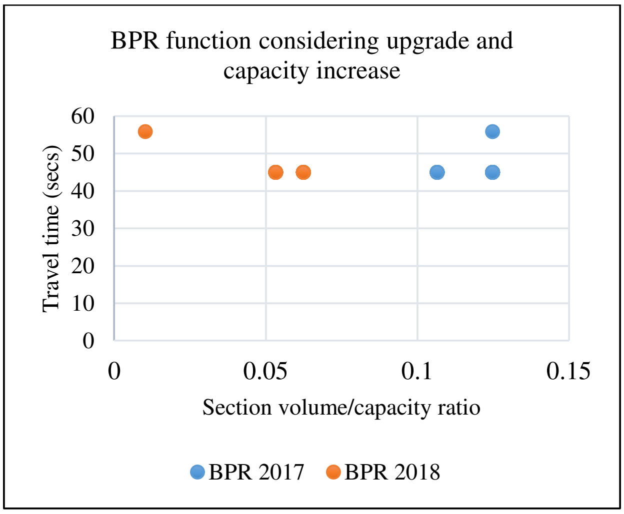

Figure 7 Change in travel time on Ugandan national roads considering upgrade and capacity increase for 37 sections

(5) Proposed intervention on a selected OD pair along the Northern corridor in East Africa

In this subsection intervention actions are proposed for all sections in the OD pair from Kampala in Uganda (origin) to Mpondwe at the Congo boarder (destination) along the Northern Corridor and the intervention policy minimising social cost was selected as the optimum. This OD pair was selected because it had links of about the same length and travel time as approximated by Google maps hence the traffic volume may remain constant on each link (Figure 8). It was approximated that one link (Kampala-Fort Portal-Mpondwe) was 432 km long and required about 6 hours and 46 minutes to traverse while the alternative second link (Kampala-Mbarara-Mpondwe) was 442 km long and required about 7 hours and 15 minutes of journey time by car. The cost of intervention actions is shown in Table 8. It was assumed that patching was done for section in condition state 2 and overlay was done for condition state 3 and 4. It was also assumed that technological improvements maintained the overlay cost at the lower bound and average cost was considered for patching. A budget level of \$10.5 million per km similar to the proposed project cost of the 95 km tolled Kampala Jinja Expressway was set (UNRA, 2018).

Figure 8 Links on the Kampala-Mpondwe OD pair in Uganda (Source: Google maps)

Table 8 Cost of intervention actions (MoWT 2016/17, UNRA 2018)

Action		Unit cost*
Repair/ Rehabilitation (A_i)	Patching ($A_{i,1}$)	(8.4-17.5)
	Overlay ($A_{i,2}$)	(280-497.5)
Upgrade (A_u)		2,360
Capacity increase (A_c)		2,360

**Value in 1,000USD/km (in 2017). Range shows value for low and high traffic roads.*

Table 9 shows link characteristics for the surveyed section of the Kampala-Mpondwe OD pair. In the setting of policy, action A_u was not considered because all sections on the Kampala-Mpondwe OD pair were paved. A_c was considered to increase capacity to 2 times. Total travel time saved was obtained as $\sum_{k=1}^{K}\{\tau^k - \tau^{k,A}\}$ and costs were not discounted since actions were assumed to be done immediately. ω was assumed to be \$20/h.[5]. Policy 1 resulted in a travel time reduction of 244.5 secs with an additional social cost of \$66.36 million while policy 2 resulted in a travel time reduction of 232.9 secs with an additional social cost of \$57.78 million compared to the do nothing policy (policy 0) (Table 10).

Table 9 Link characteristics on Kampala-Mpondwe OD pair

Link	No. of surveyed sections	No. of sections per condition state				Section (v^k/c^k) ratio	
		Condition state					
		1	2	3	4	> 1	< 1
1.Kampala-Fort Portal-Mpondwe	138	95	35	6	2	1	137
2.Kampala-Mbarara-Mpondwe	277	190	54	26	7	25	252

**In 2018, all sections for the Kampala-Mpondwe OD pair were paved*

---

[5] The monetary value of one unit of travel time in Uganda was unclear. This assumption was made based on shared car transport charges in Uganda. Uber charges about \$0.27/km.

Table 10 Social cost and travel time saved considering actions performed on sections Kampala-Mpondwe OD pair

Policy	Actions	ξ ($million)	Total Travel time saved (secs)
Policy 0	A_0	418.23	0
Policy 1	$A_i \; if \; i^k > 1$, $A_c \; if \; (v^k/c^k) > 1$	484.59	244.5
Policy 2	$A_i \; if \; i^k > 2$	476.01	232.9

4. CONCLUSIONS

This study developed a model to aid the decision process on network interventions (upgrade, condition improvement and capacity increase) by optimising social costs. Toll-free conditions were considered given that political decisions normally outweigh technical plans in reality. An empirical study was carried out on a surveyed section of the Northern corridor in East Africa specifically on the Kampala-Mpondwe OD pair. It was shown that policy 2 achieved about the same travel time reduction at a lower cost compared to policy 1 for the specific OD pair. The model can further be applied to the entire network.

REFERENCES

1) Bureau of Public Roads (BPR): Traffic Assignment Manual, U.S. Department of Commerce, Urban Planning Division, Washington D.C., 1964.
2) Federal Highway Administration (FHWA): Traffic Data Computation Pocket Guide, No. FHWA-PL-18-027, 2018.
3) Lin, K. and Lin, C.: Applying Utility Theory to Cost Allocation of Pavement Maintenance and Repair, International Journal of Pavement Research and Technology, Vol.4 No.4, pp 212-221, 2011.
4) Liu H. and Wang D., Z., W.: Modeling and solving discrete network design problem with stochastic user equilibrium, Journal of Advanced Transportation, pp 1295-1313, 2016.
5) Lu, Z., Meng, Q. and Gomes, G.: Estimating link travel time functions for heterogeneous traffic flows on freeways; Journal of Advanced Transportation. 2016; 50:1683–1698 DOI: 10.1002/atr.1423, 2016.
6) Luis G. W., Handbook of Transport Modelling, Elsevier: Handbooks in Transport, Volume 1, pp 203-220, 2008.
7) Ministry of Works and Transport (MoWT), Uganda: Annual Sector Performance Reports (ASPR); http://www.works.go.ug/document-category/jtsrw/, 2011 to 2017
8) Ministry of Works and Transport (MoWT), Uganda: Design manuals, 2010.
9) Newbery, D. M.: Cost Recovery from Optimally Designed Roads, Economica, Vol. 56, No.222, pp165-185, 1989.
10) Newbery, D. M.: Road damage externalities and road user charges, Econometrica, Vol. 56, No.2, pp295-316, 1988.
11) Northern Corridor Transit and Transport Coordination Authority (NCTTCA), http://www. http://ttcanc.org/, 2020.
12) Podgorski, K. V. and Kockelman, K. M.: Public perceptions of toll roads: A survey of the Texas perspective, Transportation Research Part A, Journal of Transport Economics and Policy, Vol. 40, No.1, pp. 888-902, 2006.
13) Small, K. A. and Winston, C.: Optimal highway durability, The American Economic Review, Vol. 78, No.3, pp. 560-569, 1988.
14) Small, K. A. and Yan, J.: The value of "value pricing" of roads: second best pricing and product differentiation, Journal of Urban Economics, Vol. 49, pp. 310-336, 2001.
15) Small, K. A., Winston, C. and Evans, C. A.: Road Work: A New Highway Pricing and Investment Policy, The Brookings Institution, Washington, D. C., 1989.
16) Transport Research Board (TRB): "Highway Capacity Manual 2000." 3rd Ed., National Research Council, Transportation Research Board, Washington, D.C., 2000.
17) Uganda National Roads Authority (UNRA), Annual Performance Report, FY2017/18, 2018.
18) US Department of Transportation (USDoT), Federal Highway Administration (FHWA): Vehicle Classification; FHWA-HRT-13-091, 2014.
19) Verhoef, E. T. and Small, K. A.: Product Differentiation on Roads: Constrained Congestion Pricing with Heterogeneous Users, Journal of Transport Economics and Policy, Vol. 38, No.1, pp. 127-156, 2004.