RCM AND AHP HYBRID MODEL FOR ROAD NETWORK MAINTENANCE PRIORITIZATION

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Abstract. Category1 defects such as potholes significantly accelerate structural deterioration and pose imminent hazards on trunk road networks. Frequent occurrences of category1 defects have increased service disruptions on trunk road networks. Road maintenance agencies are now required to effectively prioritize trunk road network category1 defects maintenance works. However, existing road maintenance prioritization methods such as value engineering and traditional expert judgment methods have limitations. Value engineering is resource and time intensive thus best suited for project level prioritization and traditional expert judgments are subjective and lack audit trails. In an attempt to address the limitations of above methods, this study presents a Reliability Centered Maintenance and Analytical Hierarchy Process based hybrid model for trunk road network maintenance prioritization. The proposed hybrid model is used to establish failure diagnostic and Multi-criteria Decision Making respectively. As a case study, the hybrid model is implemented on a trunk road network in the United Kingdom. Relevant category1 defect failure information linked to trunk road network sub-assets are extracted from databases and relevant information elicited from maintenance experts. The criticality analysis results presented show the risk priority numbers of category1 defect related failures and cost effective preventative maintenance tasks are proposed. The Analytical Hierarchy Process results are used to address the complex prioritization process. The proposed hybrid model facilitates a systematic prioritization of a large number of trunk road network category1 defect failure maintenance activities consistently.

Keywords: trunk road network, category1 defects, reliability centered maintenance, multi-criteria decision making, analytical hierarchy process.

1. Introduction

Audit Scotland (2011) reports that Scottish road maintenance funding in purchasing terms has declined by 32%, defects incidence increased by 50% and road maintenance backlog increased by 44% to approx 3.5 billion EUR within the last decade. In a bid to guarantee best value for scarce resources road maintenance agencies are required to more than ever before effectively prioritize trunk road network category1 defects related maintenance works. However, existing road maintenance prioritization techniques have limitations. Asset priority index is asset centric, value engineering is resource intensive and best suited for project level works (Clark 1999) while traditional expert judgments lack consistency and audit trails. The Swedish Transport Administration (2010) reports that multiplicity of exigencies such as extreme weathers and growing traffic have led to a higher incidence of category1 defects on trunk road networks. Category1 defects are road failings such as potholes and missing road traffic

signs that significantly accelerate structural deterioration and pose imminent hazards on pricey trunk road networks (DFT 2001). Higher incidence of category1 defects has increased the frequency of maintenance works, service interruptions on trunk road networks and exposed flaws of existing road maintenance strategies.

De la Garza *et al.* (2011) study on network-level optimization of pavement maintenance renewal strategies states that the lack of simple road maintenance decision support tools has exacerbated the failings of existing road maintenance strategies. Category1 defects occur at random across dissimilar sub-assets on trunk road networks covering several miles. Effective maintenance of category1 defects is therefore not possible with simple prioritization techniques or mere experiences. Instead more systematic procedures which match recent up comings such as dwindling funding are required. This paper presents a Reliability Centered Maintenance (RCM) and Analytical Hierarchy Process (AHP) based hybrid model for trunk

road network maintenance prioritization that can support complex multi-criteria decisions. As a case study the RCM and AHP approaches are implemented on a United Kingdom (UK) trunk road network with a focus on category1 defects related failures and the combination of the outcome of both the RCM and AHP forms the hybrid model. The Delphi approach is also used to structure, a series of serial questionnaires and controlled feedback to arrive at a consensus result on the consequences of trunk road network category1 defects related failures from trunk road maintenance experts.

This investigation focuses on trunk road network category1 defects related failures due to their high financial and human cost. For example, road defects account for 21% of road traffic accidents (Ohakwe *et al.* 2011) and road traffic accidents claim the largest toll of human life, 1.2 m deaths and 4.6 m injuries yearly (WHO 2004). The need therefore arises for new insight into category1 defect failure dynamics to mitigate risk, increase predictability and improve trunk road network service levels. The hybrid model presented in this paper attempts to model the various category1 defects failures enabling demanded trunk road network maintenance improvements. On the evidence that the modules of the hybrid model; RCM increases visibility into assets failure dynamics (Deshpande, Modak 2002) and AHP facilitates improved decision making respectively (Ishizaka, Labib 2011).

In this paper the RCM process is used to gain better insight into trunk road network category1 defects related failures, analyse risk of failures and propose best suitable preventive maintenance strategies to tackle these failures. (Deshpande, Modak 2002) applied RCM to the steel industry and reports that the RCM process improves systems functionality with significant efficiency benefits. The AHP is also used in this study to decompose complex trunk road network category1 defects maintenance prioritization decisions which entail conflicting objectives, multi criteria, disparate trunk road network sub-assets and varying category1 defects failures into a simple hierarchy. (Farhan, Fwa 2009) says AHP is fit for prioritization of road maintenance works due to its operational advantage in evaluating a large number of maintenance activities and ability to effectively provide priority assessments for road maintenance activities. However, prior empirical attention in road maintenance has been limited to pavements but this study considers other (non-carriageway) trunk road network assets.

The new development in this paper is integrating the RCM and AHP modules into a hybrid model to aid robust prioritization of a large number of category1 defect failure maintenance activities. Labib *et al.* (1998) developed an AHP and fuzzy logic based intelligent maintenance prioritization model and first proposed the use of AHP and RCM as a viable alternative and applied in Taghipour *et al.* (2010) for prioritization of medical equipment's. A rational stride is to validate the fitting of RCM and AHP as a hybrid and viable prioritization method by extending it

to a new application area, trunk road networks. This paper attempts to address the maintenance problem using a different approach. RCM and AHP have proven their worth in industry; the road maintenance industry has however been slow to respond to the potential of these methods. This is comprehensible, various industries are still yet to come to grasp with RCM and AHP techniques which are theoretically sound, understandable and matches their expectations.

2. RCM and AHP approaches

Moubray (1997) defines RCM as a technique which determines the maintenance requirement of a system and the intervals at which these is to be carried out in its operating context through a failure mode, effects and criticality analysis. RCM uses predictive and preventive maintenance activities to preserve systems serviceability to user specifications by identifying system functions, pattern and effects of function cuts and providing smarter knowledge to propose adequate maintenance task to sustain functions and mitigate risk. RCM was developed in the 1960's in response to rising maintenance cost and reduced aircraft availability linked to routine time based maintenance tasks. After its implementation, airlines recorded cost savings, avoidance and increased aircraft availability and reliability (Deshpande, Modak 2002). This is because unlike routine maintenance, RCM bases maintenance intervals on equipment state and performance data which reduces the rate of maintenance.

Other maintenance improvement approaches such as TPM and TQM were considered for this study but RCM is more critical than TPM and TQM. For example, RCM provides detailed guidance in maintenance task selection from an option of six maintenance tasks which are as follows; 1) Fault diagnosis (FD): further investigation into intrinsic failures before an operational demand, 2) Operator maintenance (OM): routine maintenance task by operators to maintain assets functionality, 3) Condition based maintenance (CBM): maintenance work that follows after measurement of asset performance data, 4) Time based maintenance (TBM): periodic maintenance tasks aimed at delaying failures, V) Breakdown based maintenance (BBM): deliberate and cost effective option to allow asset run to failure, and VI) Asset Redesign (AR): proactive effort to tackle failure by designing out failure. In addition, RCM is well structured and has a standard methodology, which assists implementation unlike TPM and TQM. RCM program may defer with various applications but the fundamental steps as outlined by (Moubray 1997) are followed below for this application of the RCM process to the UK trunk road network as shown in Section 3 below.

The AHP approach is a multi-criteria decision making (MCDM) technique which structures and solves complex strategic decision problems involving multiple criteria. Trunk road network category1 defects failure maintenance decisions are complex and strategic decisions due to their significance and number of aspects,

alternatives and stakeholders to be considered. Solving can be, preferential ranking or choosing the best option from a set of alternatives. Saaty (1980) says considering multiple criteria and structuring complex decisions simply leads to better more informed decision making. MCDM has been widely applied, Cavalcante, Costa (2006) developed a multi-criteria model of preventive maintenance and says MCDM enriches equipment maintenance process by allowing for the consideration of dissimilar and vital criteria related to the operational performance of equipment parts, and also treats existing conflicts among criteria, taking into account the preferences of the decision-maker.

MCDM techniques are divided into two main groups; Multi Alternative Decision Making (MADM) and Multi Objective Decision Making (MODM) models. The former is mostly employed in evaluation problems and the latter in design problems. This paper considers an evaluation problem; prioritization of trunk road network maintenance works thus MADM systems. A range of MADM techniques exist such as Multi-attribute utility theory (MAUT), Analytic hierarchy process (AHP), Elimination and Choice Expressing Reality (ELECTRE) and Value Engineering (VE). These MADM techniques are best suited in different context, for example MAUT depends on the axiom that decision makers are rational with ideal knowledge and capable of valid verdicts. The AHP technique however relies on the supposition that decision makers make better relative judgments than absolute judgments. Unlike MAUT and AHP, ELECTRE incorporates the fuzzy nature of decision making while VE's construct, is a multi-disciplinary environment for decision makers. After a SWOT analysis of various MADM methods as shown in Table 1 below, AHP was chosen for this study due to its unique ability to test for consistency of judgements and thousands of actual variable applications (maintenance selection, planning, forecasting and prioritization) in which the AHP results were accepted (Farhan, Fwa 2009; Forman, Gass 2004). In addition, AHP has a more relaxed rationality deduction and the threat to AHP as shown in Table 1 was compensated with the RCM module of the proposed hybrid model.

AHP is a mathematical technique developed by Thomas. L. Saaty in the 1970's (Saaty 1980). AHP entails, decomposition of a decision problem into smaller manageable units in the form of a hierarchy, pairwise comparison of hierarchy elements to assign numeric values to expert's judgments, synthesis of judgments to yield a set of overall priorities for the hierarchy, and lastly sensitivity analysis to, test the impact of results when input data is modified. Ishizaka, Labib (2009) study examined the original AHP and recent modifications but states that despite minor modifications, the original AHP remains robust and the most applied. The original AHP as developed by Saaty (1980) is implemented to the UK trunk road network considered in this study and presented in Section 4 below. The respective modules of the proposed hybrid model are fitted together and presented in Section 5.

3. Truck road network asset selection

The trunk road network considered in this study consists of over 3.387 km of roads and 3.754 structures. 19.333 events relating to maintenance of a UK trunk road network sub-assets category1 defect related failures extracted from a Computer Maintenance Management System and relevant information from regulatory and operations manuals and road maintenance experts was used for the RCM analysis. The sub-assets investigated in this study are as follows: Road Restrain Systems (RRS), Road Lightings (RL), Carriageway (CW), Road Markings (RM), Road Traffic Signs (RTS), Traffic Lights (TL), Studs (S), Kerbs and Edgings (K&E), Covers Graters and Frames (CG&F), Fences Wall Screens & Noise Barriers (FWSNB), Drain and Sewers (D&S), Hard Shoulder (HS), Established Trees and Shrubs (ET&S), Geotechnical Assets (GT), Speed Cameras (SC), Linear Drainage Systems (LDS), Road Side Telephones (RST), Closed Circuit Television (CCTV) and Variable Message Signs (VMS).

Table 1. Comparative Analysis of MADM Techniques

MADM	Strength	Weaknesses	Opportunities	Threats
MAUT	Strong theoretical insight and takes uncertainty into account	Complex, best applied by experts on major projects with time and expertise	Effectively used as a standalone and suitable for high cost (financial and human) decision problems	Too rigid, bottom-up method and few real application
ELECTRE	Ability to incorporate the fuzzy nature of decision making and can make use of less precise inputs	Algorithms used are not well understood by decision makers and not suitable in decision workshop mode	It has seen recent methodological developments and retains a good future	Strongly criticized for lack of axiomatic foundations
AHP	Unique ability to test for consistency and sensitivity to test robustness of results	Pairwise comparison of more than 20 options may become a extensive task	Software's to aid application and judgmental process is far more intuitive and appealing	Lacks robustness when applied in isolation
VE	Spurs multidisciplinary team working and creative thinking	Entails a certain amount of expense and unsuitable for program level issues	Organized process, impressive history and meets required function and quality level	Requires top level buy in and linked change often resisted

Source: (Belton, Stewart 2002; Clark 1999; Forman, Gass 2004).

3.1. RCM criticality analysis

Failure Mode and Effects Analysis (FMEA) is conducted on the selected assets. The FMEA is the first step of the RCM process. FMEA is an analytical and engineering method that enables a better understanding of a systems failure mechanism and reduces failure by eliminating or designing out root cause of failures. The purpose of FMEA is to determine systems failure modes; all the ways that components of a system can fail and to identify their resulting effects on the rest of the systems performance. Failure Mode and Effects Analysis (FMEA) was used in this study to gain fresh insight into causes of trunk road network category1 defect failures because a systems failure or operating pattern such as trunk road networks changes over time due to variables such as weather or human element. After the Failure Mode and Effects Analysis (FMEA) of the UK trunk road network a total of 23 functions, 38 functional failures and 54 failure modes were identified from our FMEA. A function is the original intent for which an asset was acquired. As an example Road Lights (RL) are acquired to enhance traffic visibility at night hours. Whenever a sub-asset such as Studs (S) which is acquired to provide guidance in adverse driving conditions fails to provide such guidance or fails to provide such function to user's specification either due to frost action or design error, that sub-asset is said to have functionally failed. This functional failure of a stud can lead to poor delineation of traffic lanes and poor road user judgments that increases likelihood of accidents, failure effect.

Following the FMEA, a failure criticality analysis is further conducted to determine the risk associated with identified failure modes. The criticality analysis of the risk associated to pre-determine failure modes are ranked using their risk priority numbers. The risk priority number is the product of frequency, severity and detectability metrics of an individual failure mode. For example, Road Restrain Systems (RRS) which are acquired to provide fail safe mechanism had a failure mode tagged as missing. When the road restrain system is not in its installed position and this increases severity in vehicle passenger cell when a vehicle swerves. In other to determine the risk priority number of this failure mode the likelihood of occurrence (frequency), consequence of its occurrence (severity) and probability that it can be detected prior to occurrence (detectability) have to be calculated. The frequency, severity and detectability values for failure modes derived in this study were estimated by road maintenance experts from ranking tables used for this study with values ranging from 1 to 10 and corresponding to description of a failure. As an example, for the frequency metric that a failure mode will not occur, probably occurs and certain to occur corresponded to 1, 5 and 10 on the ranking table respectively. Once the frequency, severity and detectability values were derived consensus of the metrics were multiplied to arrive at the risk priority numbers of each failure mode. The Risk Priority Numbers of failure modes enables RCM prioritize catastrophic failures above less catastrophic failures. After the analysis sub-assets such as Road Lights (RL) and Road Restrain System (RRS) had high risk priority numbers above 300, more catastrophic failures. However sub-assets such as Studs (S) and Traffic Lights (TL) had risk priority numbers less than 150, less catastrophic failures.

3.2. Maintenance task selection

The last step of the RCM application is a RCM logic decision tree to assign appropriate preventive maintenance strategies to tackle failures identified. Effective maintenance is aimed at performing maintenance in an optimal way to minimize total cost for operation and maintenance. RCM uses the decision logic to find an optimal balance between preventive and corrective maintenance tasks because determining this subjectively through traditional expert judgements is difficult. For example, high risk trunk road network failure modes such as Road Restrain System (RRS) with RPN above 300 must be prevented from occurring with preventive maintenance because of their catastrophic consequence on safety, operations and the environment and attendant cost in the form of claims from accidents. Preventive maintenance is maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an asset. On the other hand, corrective maintenance which is currently synonymous with category1 defect related failures is maintenance executed after a failure has become evident. Subjectively there are disparities of opinions on the best approach to achieve effective maintenance but maintenance task selection using the RCM logic decision solves that.

The decision tree consists of 7 Yes or No questions which are presented to road maintenance experts. The RCM logic decision tree developed by Moubray (1997) was used for the maintenance task selection segment of this RCM analysis. A sample question is (Question 2), Does an inherent failure mode, damaged Studs (S) become evident to inspectors. The answer to this is was a no. Experts adduced so because inspectors drive at an average speed of 35 m/h during inspection regimes which are too fast to visually ascertain its state, inspectors have larger sized assets they concentrate on while in motion and there is no metric to determine impact of studs to drive comfort. In the decision tree a no in Question 2 leads to Question 3 but a yes to Question 2 would have led to 1 out of the 6 maintenance task that RCM analysis proposes as mentioned above in Section 2. After conducting the maintenance task selection, the RCM logic decision tree proposed 5 Fault diagnosis (FD), 26 Operator Maintenance (OM), 10 Condition Based Maintenance (CBM), 4 Time Based Maintenance (TBM), 6 Breakdown Based Maintenance (BBM) and 2 Asset Redesign (RA) tasks.

Results

The results of the RCM technique implemented to a UK trunk road network as a case study depicts varying risk priority numbers for the identified 54 failure modes. The findings show that sub-assets such as Road Lights (RL)

had failure modes with risk priority numbers above 370 and sub-assets such as Studs (S) had failure modes with risk priority numbers (RPN) lower than 150. These disparate risk priority numbers are used as a basis to develop a ranking scale for reclassification of trunk road network category1 defect related failures in to Types 1 to 4 as shown in Fig. 1 below. Where, Type 1 corresponds to minor failures with RPN of 001 to 100, Type 2 tolerable failures with RPN of 101 to 200, Type 3 incipient failures with RPN of 201 to 300 and Type 4 catastrophic failures with RPN of 301 to 400. This method is adaptable and focuses maintenance attention to high risk (Type) trunk road network failures which would have the most impact on network availability. The percentage occurrence of minor, tolerable, incipient and catastrophic failures across the UK trunk road network is shown in Fig. 1 below.

4. AHP application to trunk road network

Step 1: Decomposition of decision problem

The trunk road network category1 defect maintenance prioritization problem involving disparate criteria and
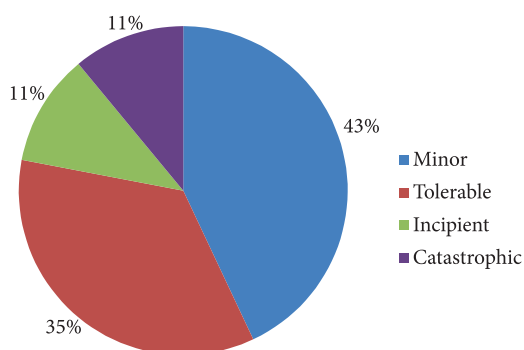

Fig. 1. Percentage distribution of reclassified failures across UK trunk road network

Table 2. Fundamental Scale for Pairwise Comparisons

How important is A relative to B	Preference Index assigned
Equally important	1
Moderately more important	3
Strongly more important	5
Very Strongly more important	7
Overwhelmingly more important	9

trunk road network sub-assets are decomposed into a three level hierarchy using the multi criteria approach as shown in Fig. 2 below. Level 1 is the objective (maintenance priority), Level 2 state the criteria considered for prioritization of trunk road network, information in level 2 are defined through careful consultation with experts using the Delphi elicitation approach and level 3 are the trunk road network sub-assets. The criteria on Level 2 of the hierarchy as shown below in Fig. 2 brought to the fore stakeholder's mostly affected by trunk road network maintenance decisions. The function criterion is directly linked to the sub-assets, road users and trunk road maintenance operators who manage performance based road contracts. The risk criterion is directly linked to road users and road agencies that bear responsibility and pay claims for catastrophic events. The regulation criterion is linked to trunk road network category1 defects maintenance legislation. Utilization and downtime criteria to trunk road network sub-assets and maintenance requirement to sub-assets and operators.

Step 2: Pairwise comparison

The AHP uses a fundamental scale shown in Table 2 below to pairwise compare elements on each level of the hierarchy. Saaty (1980) suggest in Table 2 that index values of 2, 4, 6 and 8 can be assigned to intermediate values.

Road maintenance experts were consulted through questionnaires and telephone conversations to pairwise compare the elements on Level 2 and the elements in Level 3 with respect to Level 2. Pairwise comparison approach is used instead of direct allocation because of the fundamental principle to make it easier for experts to assess n elements (where $n > 2$) simultaneously at a time and to ensure consistency in cross checking the differences of pairwise comparisons. From the results obtained from the questionnaire survey, it was observed that level 3 expert's opinion on road lights (RL) is rated 'strongly more important' with index value 5 (Table 2) when compared against road markings (RM) with respect to the function criterion on Level 2 as shown in column 3 row 5 in Table 3.

The result of each set of pairwise comparison as shown in Table 3 below is a $n \times n$ positive reciprocal matrix $X = (a_{ij})$ where a_{ij} is the element of row i column j (comparison between sub-asset i and j), $a_{ji} = \dfrac{1}{a_{ij}}$ for all $i, j = 1, ..., n$ and $a_{ij} \geq 0$ for all $i, j = 1, ..., n$ and the matrix comes out in the form shown below in Eq (1).
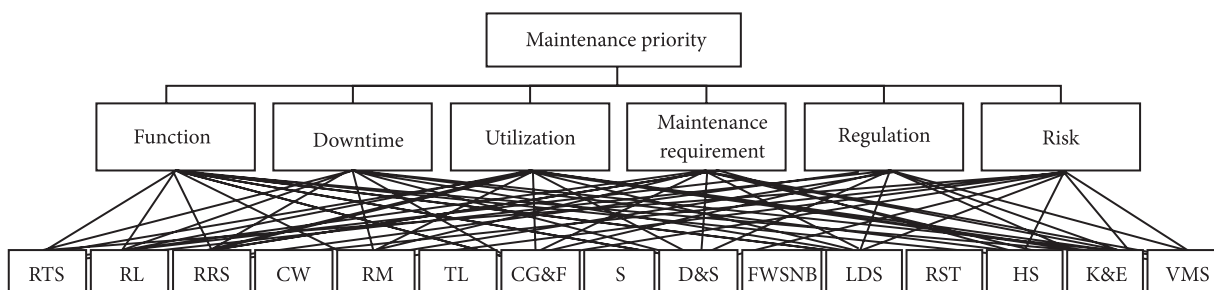

Fig. 2. Decomposition of UK Trunk road network assets

$$X = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ \dfrac{1}{a_{12}} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \dfrac{1}{a_{1n}} & \dfrac{1}{2_{an}} & \cdots & 1 \end{bmatrix}. \qquad (1)$$

Since level 3 experts' opinion on road lights (RL) when compared against road markings (RM) with respect to the function criterion on Level 2 was 5/1 the reciprocal 1/5 was then filled in to the matrix when road marking (RM) was compared against road lights (RL) as shown in Table 3 below. Positive reciprocal matrices have an advantage of reducing time to pairwise compare alternatives by 50% in this case it reduced the comparisons from 1350 to 675.

Step 3: Weights valuation

Step 3.1: Thereafter the traditional AHP eigenvector method is used to calculate relative weights of elements in the $n \times n$ matrix. Lean square and geometric mean methods exist for calculating relative weights of elements. However, Dijkstra (2010) study on extraction of weights from pairwise comparison matrices states that mathematical proof shows that there is no clear difference between these methods because they invariably yield the same results. In addition, the eigenvector method has a unique ability to measure the consistency of the matrix thus expert verdicts.

A numerical example of how the relative weights priority of sub-assets is derived is presented. In this illustration, the entries were multiplied in each row of the matrix and the nth root of the product is estimated using the expression in Eq (2).

$$n^{\text{th}} \text{ root product} = \sqrt[n]{a_{11} \times a_{12} \times a_{13} \times \dots \times a_{1n}}, \qquad (2)$$

where $n = 15$, which represents the number of sub-assets. The resulting 15th roots for rows 2 and 3 of the $n \times n$ matrix shown in Table 3 below equals to 0.8128 and 0.3314 respectively. For accuracy of the eigenvector the relative weights is normalized to ensure that the values add up to 1 for further analysis using Eq (3).

$$\frac{n^{\text{th}} \text{ root r of product}}{\sum n^{\text{th}} \text{ root of product } n}. \qquad (3)$$

The same process was applied to Level 2 elements (criteria) of the hierarchy shown earlier in Fig. 2 to derive the eigenvector (ω) of criteria as shown in the eigenvector column of Table 3. The resulting eigenvector for row 2 (ω_2) and 3 (ω_3) of the $n \times n$ matrix in Table 3 below is estimated as 0.0374 and 0.0152 respectively.

Step 3.2: Consistency of judgements

For consistency the ratio (*CR*) is calculated using Eq (4), Saaty (1980) concept which has been used the most in applications. Saaty (1980) also states that a consistency ratio

Table 3. Pairwise comparison reciprocal matrix estimates for 15 trunk road network sub-assets

Function	RTS	RRS	RL	CW	RM	TL	CG&F	S	D&S	FWSNB	LDS	RTS	HS	K&E	VMS	n^{th} root of product	Eugine vectors	Product	Ratio
RTS	1	1/2	3	5	1/5	1	3	1/7	1/3	1/7	1/2	1/7	1/2	1/7	1/2	0.5008	0.0230	0.3764	16.3522
RRS	2	1	5	6	1	3	5	1/4	1/5	1/6	2	1/8	1/6	1/7	1	0.8128	0.0374	0.6633	17.7539
RL	1/3	1/5	1	3	1/5	1	2	1/9	1/5	1/7	1/3	1/7	1/7	1/9	1/3	0.3314	0.0152	0.2507	16.4582
CW	1/5	1/6	1/3	1	1/8	1/6	1/5	1/8	1/7	1/6	1/5	1/8	1/5	1/8	1/4	0.1945	0.0089	0.1620	18.1183
RM	5	1	5	8	1	4	4	1/5	1/2	1/2	2	1/4	1/2	1/4	1	1.1659	0.0536	0.8793	16.4075
TL	1	1/3	1	6	1/4	1	1	1/5	1/4	1/3	1/2	1/5	1/3	1/5	1	0.5204	0.0239	0.3941	16.4771
CG&F	1/3	1/5	1/2	5	1/4	1	1	1/7	1/3	1/4	1/4	1/7	1/5	1/6	1/4	0.3504	0.0161	0.2789	17.3158
S	7	4	9	8	5	5	7	1	4	2	3	1/2	1	1/2	4	2.8963	0.1331	2.1520	16.1639
D&S	3	5	5	3	2	4	3	1/4	1	1/4	1	1/6	1/2	1/4	2	1.2620	0.0580	0.9949	17.1495
FWSNB	7	6	7	6	2	3	4	1/2	4	1	3	1/3	1	4	4	2.5632	0.1179	2.2014	18.6843
LDS	2	1/2	3	5	1/2	2	4	1/3	1	1/3	1	1/5	1/3	1/6	3	0.9046	0.0416	0.6792	16.3340
RTS	7	8	7	8	4	5	7	2	6	3	5	1	5	2	5	4.3630	0.2006	3.3880	16.8938
HS	5	6	7	5	2	3	5	1	2	1	3	1/5	1	1/3	3	2.0191	0.0928	1.5291	16.4756
K&E	7	7	9	8	4	5	6	2	4	1/4	6	1/2	3	1	3	3.0946	0.1422	2.4671	17.3437
VMS	2	1	3	4	1	1	4	1/4	1/2	1/4	1/3	1/5	1/3	1/3	1	0.7759	0.0357	0.5665	15.8857
																21.76	1.00		16.92

(*CR*) of 0.10 or less is a proof of valid judgment but a *CR* larger than 0.10 means inconsistencies exist.

$$CR = \frac{CI}{RI} \text{ and } CI = \frac{\lambda_{\max} - n}{n - 1}, \qquad (4)$$

where *CI* – consistency index; *RI* – random index (average value of *CI* gotten from 500 pairwise comparison matrices whose entries were randomly generated using the 1 to 9 scale shown in Table 2 above). *RI* is a standard figure for different values of *n* as shown in Table 4 below though various other simulations have been run by scientists, (Ishizaka, Labib 2011) review of AHP's methodological development says variances are negligible.

To get *CR* for the $n \times n$ matrix shown in Table 3 above, $\lambda_{\max}$ is calculated initially from the matrix and the AHP theory says if *X* is a pairwise comparison matrix of the size of *n*, $\lambda_{\max}$ is $\geq n$. Where $\lambda_{\max}$ is the principal eigenvalue of matrix calculated from the $n \times n$ matric using Eq (5).

$$\lambda_{\max} = \frac{\sum ratio}{n}. \qquad (5)$$

Where, the ratio is obtained using the illustration in Eq (6):

$$\frac{\text{Product}\left(X\omega_i\right)}{\text{Eigenevector of order } n}, \qquad (6)$$

where $i = 1, ..., n$, and the product $(X\omega_i)$ is the sum total of multiplying the elements of the $n \times n$ matrix by the corresponding eigenvector of the order of n as illustrated in Eq (7):

$$\sum \left(1 \times \omega_1\right) + \left(a_{12} \times \omega_2\right), \; ..., + \left(a_n \times \omega_n\right). \qquad (7)$$

Therefore for accuracy of calculation, the $n \times n$ matrix is calculated as shown in Table 3 above using Eqs (3)–(7). As an illustration, using Eq (7), the product $(X\omega)$ for row 2 of the $n \times n$ matrix shown in Table 3 above is estimated to be 0.6633. Using Eq (6), the ratio for row 2 of the $n \times n$ matrix shown in Table 3 above is given as 17.7539 by dividing 0.6633 and 0.0374. Therefore $\lambda_{\max}$ is calculated for the $n \times n$ matrix using Eq (5) as shown below

$$\lambda_{\max} = \frac{353.8135}{15} = 16.9209.$$

Since $n = 15$ and the *CI* value is estimated using Eq (4) and the resulting value is given as

$$CI = \frac{16.9209 - 15}{15 - 1} = 0.1372.$$

Substituting 1.59 for *RI* when $n = 15$ from Table 4 above, the calculated *CR* value is given as 0.0863, and since it is less than 0.10 it is a proof of valid judgment.

Step 4: Weights aggregation

The last step of the AHP process, the relative weights of decision elements is aggregated to obtain global weights as follows with Eq (8) below:

$$G_i^s = \sum_{j=1}^{j=c} G_{ij}^s G_j^a, \qquad (8)$$

where $i = 1, ..., n$; G_{ij}^s – the global weight of sub-set *i*; *c* – number of criteria; *n* – number of alternatives. The global weight G_{ij}^s equal weight of alternative (sub-asset) *i* associated to criteria (risk, function…) *j* and G_j^a is the weight of criteria *j*.

The global weights are then used to rank the alternatives thus prioritize trunk road network sub-assets for maintenance. After the calculation, Covers Graters and Frames (CG&F) had a global weight of 0.1028 thus a higher maintenance priority than Road Lights (RL) with 0.0574 and Road Traffic Signs (RTS) with 0.0425.

5. Fitted trunk road network maintenance prioritization model

The RCM and AHP modules presented in Sections 3 and 4 above are then fitted into a hybrid model. Level's 1, 2 and 3 of the hierarchy presented in Fig. 2 remains unchanged but a fourth level is introduced under the third level to fit the model. The fourth level consists of trunk road network failures which are reclassified into Types 1 to 4 according to their RPN from the RCM module presented in Section 4 above as against existing generic classification as category1. To illustrate the fitted model the failure types to sub-assets are randomly allocated to minimize allocation bias and balance both known and unknown factors that can influence the incidence of different failure Types across trunk road network sub-assets. Road restrain systems was allocated a Type 4 failure and road lights a Type 2 failure and others respectively. After the failures were allocated the failure types are normalized as shown in Table 5 below and synthesized the result to the global priorities to arrive at final prioritization weights shown in the graph in Fig. 3.

The proposed hybrid model has a unique characteristic, it is highly adaptable and suffices for both project level (above 350 000 EUR) and program level (below 350 000 EUR) trunk road network maintenance works. Category1 defect related failures maintenance works fall under program level maintenance works. The model without the fourth level of the hierarchy is in a project level mode but once the fourth level, failure Types are fitted, it enters the program level mode. The proposed hybrid approach presented in this paper has two limitations which is the likely ambiguity of English used in questionnaires for elicitation of road maintenance expert judgments and slight

Table 4. Random index values for different matrix orders (Coyle 2004)

When $n =$	1–2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

sentient behavior exhibited when the model is applied across the program and project modes but has the the under listed capabilities:

    I. Facilitate system thinking in to trunk road network failures maintenance.

    II. Decompose complex trunk road network maintenance prioritization into simple manageable bits.

    III. Prioritize a large number of trunk road network maintenance alternatives in a consistent manner.

    IV. Provide audit trails for decisions and aid collaboration between specialist maintenance teams.

Results

In the project mode, the hybrid model illustration results show that carriageways (CW) with global weight of 0.1560 is to be prioritized highest closely followed by covers, graters and frames (CG&F) with 0.1028. Linear drainage systems (LDS) with a global weight of 0.0411 are prioritized least closely followed by road traffic signs (RTS) with 0.0425. However, in the program mode, the model illustration shows that carriageways (CW) with Type 4 failure and final weight of 0.2585 is prioritized highest closely followed by Hard Shoulders (HS) with Type 4 failure and final weight of 0.1575 above covers, graters and frames (CG&F) with a Type 2 failure and final weight of 0.1541. Road side telephone (RST) with Type 1 failure and final weight of 0.0824 is to be prioritized least and road markings (RM) a little higher with a Type 1 failure and final weight off 0.0923. A further analysis of the hybrid model illustration results reveals that the risk criteria, risk posed by category1 defect failures to road users and trunk road networks had the highest priority with a weight of 0.3406, closely followed by the function criteria. The function criteria earlier defined in Section 3.2 above had a weight of 0.2104. The function criteria's maintenance priority was higher than that of downtime with a weight of 0.1263 due to the linkage between the two criteria. When a sub-asset is in function, downtime is absent but once a sub-asset has functionally failed then downtime creeps and begins to build up till it is restored back online. Regulation criteria with a weight of 0.6609 had the least maintenance priority. This is attributable to current regulation centric maintenance strategies which have failed to meet the ever increasing expectations of road users. Maintenance requirement had a weight of 0.1325 slightly higher than downtime. It is pertinent to note that 48% of the maintenance task selection from the RCM analysis was Operator Maintenance which cuts downtime thus the appreciable weight of the maintenance requirement criteria.

6. Conclusions

In this paper the Reliability Centered Maintenance and Analytical Hierarchy Process hybrid model for trunk road network maintenance prioritization is presented. To illustrate the model adequacy, trunk road network category1 defect related failures from the United Kingdom is used. The Reliability Centered Maintenance logic and related risk priority numbers of identified failures is used

Table 5. Normalized failure types

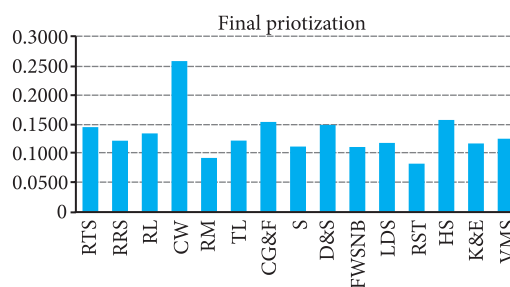| Failure type	1	2	3	4
Normalized score	0.0256	0.0513	0.0769	0.1026

Fig. 3. Final prioritization weights for trunk road network sub-assets and attending failures

to reclassify failures into catastrophic (Type 4), incipient (Type 3), tolerable (Type 2) and minor (Type 1) respectively. The reclassification focuses maintenance resources to high risk trunk road network failures and Type 1 failures which make up 43% of all failures. The Analytical Hierarchy Process module is used to support the analysis of criteria critical to trunk road network maintenance decisions, decomposition of complex trunk road network maintenance prioritization processes into simpler manageable units and transformation of judgments into weights. The fitted hybrid model provides road authorities with a scientifically valid method that can systematically prioritize a large number of disparate trunk road network maintenance works in a consistent manner and with much needed audits trails. Furthermore, the proposed hybrid model handles both qualitative and quantitative data and is suitable for both project and program level trunk road network maintenance works. This outcome of this analysis is expected to provide effective monitoring and identification of trunk road network failure dynamics, provide anticipated information on maintenance of non-carriageway assets and a platform to improve existing trunk network maintenance prioritization processes to increase efficiency of road authorities.

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