Evaluation of the Effects of Maintenance and Rehabilitation Projects on Road User Costs via HDM-4 Software

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Abstract

Rapid growth in a number of vehicles on roadways accelerates pavement deterioration trends. Pavement inefficiency in carrying the applied load from passing vehicles results in spending significant costs on continues Maintenance and Rehabilitation (M&R) treatments. Lane closure owing to the implementation of M&R operations incurs enormous costs on road users. The research aimed to calculate, and compare Road Agency Costs (RACs) with Road User Costs (RUCs) resulted from certain types of M&R interventions on a selected roads network located in eastern part of Iran. RUCs are divided into two main categories; namely, Vehicles Operational Cost (VOC) and Travel Time Cost (TTC). The main contribution of the paper was to demonstrate the importance of RUCs in long-term economic analysis and planning of future M&R activities. A number of complicated parameters are involved in RUC estimation. The latter is the primary reason for excluding RUCs in the economic analysis. Towards this end, the HDM-4 Software was employed to calculate costs using localized data. Calibrating the HDM-4 as well as collecting the required information, the long-term effects of preservation alternatives associated with their costs were evaluated and compared. Results showed that RUCs were approximately 10 times higher than RACs on each route of the selected roads network. This revealed the importance of RUC in the Life Cycle Cost Analysis (LLCA) of different M&R actions tale place on highways. Hence, taking into account RUCs within analysis approaches would yield propose the most appropriate and cost-effective M&R alternative. Also, it was concluded that traffic composition and the number of Equivalent Single Axle Loads (ESALs) in the analysis period were contributing factors to RUCs calculation. In addition, owing to the long queue formation because of road obstruction, VOCs were always higher than increased TTCs, illustrating the importance of traffic volume and composition.

Keywords: Road user costs, HDM-4 Software, life cycle cost analysis, maintenance and rehabilitation

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1. Introduction

Due to the restricted budget allocated to road agencies and the significant increase in a number of road users, departments of transportation have been persuaded to develop and implement efficient Pavement Management Systems (PMSs) to save money and time [Medury and Madant, 2013]. Nowadays, many highway engineers have utilized economic tools and concepts in project analysis. In doing so, life cycle costs and benefits derived from the establishment of different Maintenance and Rehabilitation (M&R) projects have been estimated [Abdollahzadeh, 2011]. PMSs consist of data collection and entrance into software or spreadsheets so that Road Agency Costs (RACs) and Road User Costs (RUCs) are calculated [Harvey, Wang and Lea, 2014]. Life Cycle Cost Analysis (LCCA) is an evaluation tool taking into account the cost-efficiency of different M&R alternatives based upon Net Present Values (NPVs) [Caltrans, 2013]. Various types of parameters and costs are considered in LCCA to propose the best M&R option. These costs incudes initial construction costs, future M&R costs, user costs and environmental costs and residual values of pavements. LCCA has been adopted as an efficient procedure to examine the sustainability and cost-effectiveness of public infrastructure investments, and has developed since the 1950s [Ozbay et al. 2004]. As the contribution of LCCA to transportations projects was recognized, the importance of RUCs was taken into consideration by researchers. RUC is a fundamental parameter in decision-making within different stages of construction and maintenance projects. the estimation of RUCs would provide engineers with required information regarding traffic congestion over work zones and selection of the most cost-effective M&R alternative [Qin and Cultler, 2013].

The research was carried out with the aim to calculate RUCs while M&R projects are performed on roads networks. In doing so, the Highway Development and Management (HDM-4) software based on LCCA concepts was used. RUCs are divided into two main categories; namely, costs incurred on vehicles over work zones and costs of time resulted from delay faced by users. The mentioned subdivisions are subjected to various constraints in their collection. In the number of research works in the context of LCCA, it was reported that transportation departments neglected the RUCs or assumed equal values for any types of M&R options due to inability to calculate and collect precise data [Ozbay et al. 2004, ACPA, 2011 and Babashamsi et al. 2016].

There must be a difference between work zones' areas and lane blockage duration, as a result of the application of various M&R projects. This research was carried out to collect required localized data for Iran to illustrate the significant effects of RUC in M&R operations and the fact that ignorance of RUC in LCCA procedure is completely flawed. With respect to Ozbay et al. (2004), available guidelines and assumptions regarding LCCA, pave the way to conduct the state-of-the-practice LCCA. Since there has been a number of differences between state-of-the-practic LCCA and sate-of–the–art LCCA; one step to achieve the latter is to consider users and social cost providing required data bank and reveal the importance and the scale of RUCs.

The HDM-4 software was used to calculate RUCs by collecting required localized data and associated unit costs on a selected roads network. The roads network includes five primary highways with the total length of about 450 Km located in South Khorasan Province , Iran. The principal of the software is based on the concept of LCCA. HDM-4 Software is able to calculate present amounts of RUCs and RACs by predicting the performance of different M&R activities in the defined analysis period using defined discount rate [Kerali, 2002]. The research was carried out representing basic elements of HDM-4 Software and RUC estimation methods. Furthermore, the review pertaining to conducted studies was outlined. In the next step, various types of pavement performance indicators were collected and the homogenous sections were created. Then, required M&R alternatives were proposed, and localized data for the HDM-4 software was collected and presented. Moreover, the forth section was devoted to analyze and compare RUCs with RACs on the selected roads network. In the last section, conclusions were drawn with respect to the importance of RUC calculation, and its effect on the economic efficiency of M&R projects.

2. Research Background

In this section, the components of HDM-4 and RUC calculation were explained briefly. Moreover, a review of conducted studies was provided regarding HMD-4 application and RUC impacts corresponded to the implementation of M&R operations.

2.1 HDM-4 Software

HDM-4 is a decision-making tool developed by World Bank being able to evaluate the cost-effectiveness of various M&R treatments on highways. HDM-4 utilizes four groups of models; namely, Road Deterioration (RD), Works Effect (WE), Road User Effect (RUE) and Social-Environmental Effect (SEE). In the research, RUE models were applied, specifically.

In 2005, a research was carried out to compare technical and economic characteristics of flexible and rigid pavements using HDM-4 models [Javadian, 2005]. The latter confirmed the potential of the software in the pavement analysis. In 2006, a pavement management model was developed using HDM-4 software and Analytical Hierarchy Process (AHP) [Saffarzadeh, Kavussi and Bagheri Sari, 2006]. HDM-4 was utilized to provide a list of prioritized M&R projects with regard to determined NPVs. By means of AHP method, the decision-making process was obtained. In 2013, the effects of different M&R operations on fuel consumption costs were studied [Fakhri and Shourmoyej, 2013]. It was concluded that vehicle fuel consumption was in direct relationship with pavement roughness. Results indicated that among the selected M&R activities, the implementation of crack sealing and patching had no effect on vehicles' fuel consumption. However, fundamental preservation projects reduced relevant costs significantly. Again, in 2013, the emission models of HDM-4 were calibrated for India [Prasad, Swamy and Tiwari, 2013]. The sensitivity analysis was performed on models to distinguish effective parameters. It was revealed that the pavement slope, the vehicle operational weight, and age were the most sensitive factors in models. In 2014, results obtained by two software regarding optimal budget allocation was investigated in the state of Tennessee [Sen et al. 2014]. The employed software was HMD-4 and Highway Pavement Management Application (HPMA). Outcomes demonstrated that accurate budget assignment could be achieved using HPMA. In 2015, the modification of calibration coefficient related to crack initiation was undertaken [Ognjenovic, Krakutovski, and Vatin, 2015]. It was concluded that application of calibrated coefficients led to more accurate outcomes. In 2016, a research was conducted using the HDM-4 software as a method to provide road agencies with appropriate M&R techniques and planning [Kavussi, Semnarshad and Saffarzadeh, 2016]. A sensitivity analysis and optimization were carried out with respect to various discount rates and constraints, respectively. Apart from showing the importance of the value of discount rate, a enormous financial savingwas achieved by proposed M&R programs.

2.2 Road User Costs

The RUC is a cost incurred on road users due to maintenance projects implemented on highways [Daniels, Ellis, and Stockton, 1999]. HDM-4 calculates RUCs using direct and indirect costs. RUCs are divided into four main categories; namely, VOCs, Travel Time Costs (TTCs), accidents costs and emission costs [Kerali, 2002]. As for accident costs, it relates to costs of death and injuries as well as property damages. Emission costs include environmental contamination impacts such as air and noise pollution over work zones. Accident and emission costs are difficult to gauge owing to the lack of reliable data in Iran. Therefore, VOCs and TTCs were calculated and discussed in the research. VOCs are the cost associated with ownership and operating vehicles, and TTC is a monetize delay experienced by passengers [Qin and Cultler, 2013].

Several research works have been done addressing RUC estimation. In 2003, The American Association of State Highway and Transportation Officials (AASHTO) published a book, including the detailed procedure for RUC calculation [AASHTO, 2003]. Based on the survey performed by Ozbay et al. in the United Satates of America (USA), it was reported that almost none of the USA Departments of Transportation (DOTs) took user costs into consideration in 1984, while in 2001 approximately 70 percent of DOTs consider RUC in LCCA procedure. Also since the LCCA input parameter such as inflation rates, discount rate and analysis period have always been associated with variation and uncertainty the survey was carried out to provide the more reliable range for those criteria [Ozbay et al. (2004)]. During last decade, various approaches and software (e.g. MicroBENCOST, Queue and User Cost Program of Work Zone (QUEWZ), QuickZone, Kentucky User Cost Program (KyUCP), Arizona RUC Model) have been adopted by different departments of transportation in the United States of America to measure RUCs and provide reliable results [Zhu, 2008].

Pavement roughness has been recognized as a factor affecting ride quality which can increase the VOCs since passengers and vehicles are highly affected by surface roughness. With regard to carried out research in the context of road roughness, it was concluded that initial roughness of a pavement would result in reduced RUCs [Gillespie and McGhee, 2007]. Moreover, using concepts of LLCC and comparing the costs, it was revealed that lane closure duration would result in an increase in RACs and RUCs. Considering the importance of road roughness on RUCs, further research was carried out in connection with the relationship between roughness and user costs. In doing so, the LCCA approach was considered, and various M&R treatments were selected. It was claimed that the road roughness would have a direct impact on user costs which consists of fuel consumption (VOCs), vehicle repair and maintenance costs, depreciation and tire wear costs. Those elements were modeled using appropriate methods, and IRI was predicted using Mechanistic-Empirical Pavement Design Guide (MEPDG). Outcomes proved that variation in roughness resulted in an increase in user costs. Chief among the causes of increase in RUCs was vehicle repair and maintenance costs. Finally, from a sustainability standpoint, it was revealed that the increase in the quality of highway M&R candidates caused a reduction in RUCs seeing that better preservation techniques would yield road users drive on smoother pavements during the highway service life [Islam and Buttlar, 2012].

Recently, a Multi-Objective Decision-Aid Tool (MODAT) was developed proposing three objectives; namely, minimization of RACs and RUCs as well as maximization of the pavements' residual value [Meneses and Ferreira, 2010]. The provided tool was able to combine a number of objectives into a single optimization model by Pareto optimal solution. A Genetic Algorithm (GA) was used to solve the model using weighting sum method. It was concluded that RUCs affected the decision-making process more than RACs. The application of the method to main roads network located in Portugal validated the outcomes, obtained by the proposed model. With this regard, the model could be applied to bridge network where multiple objective decision-making procedures exist [Meneses and Ferreira, 2013]. In 2012, a new LCCA system, based on optimization techniques were developed entitled

"OPTPAV" [Santos and Ferreira, 2012]. The provided PMS, considered pavement performance as well. The results of its implementation showed that the method was able to select appropriate and cost-effective M&R programs. The analysis system not only considered pavement design attributes, but it also interpreted the future costs of M&R projects, RUCs and pavement salvage values.

Furthermore, in 2012, the further analysis was performed on OPTPAV management system [Ferreira and Santos, 2012]. The sensitivity analysis was carried out on discount rates and RUCs. Results indicated that RUCs behaved differently in every condition, and depended on other input data. In addition to this, in another research work, the identical sensitivity analysis was performed to investigate the effects of the change in discount rates on total costs including the construction costs, M&R costs and RUCs, and deducting residual values of the pavement [Santos and Ferreira, 2013]. It was concluded that as discount rates increased, the total costs decreased. In addition to these, using HDM-4 models, the RUCs were calculated by considering RUE and RD models of HDM-4. The results were compared with Road User Cost Knowledge System (ROCKS), and it was concluded that HDM-4 results regarding RUC calculation were accurate [Das A, Koshey and Pradeep, 2013]. Later in 2014, the HDM-4 software was used to propose the most cost-effective M&R options and to calculate RUCs, RACs and fuel consumption [Onyango et al. 2014]. As for the RUCs and RACs, it was determined that RUCs for the selected state highway was roughly double that of the selected interstate highway. It was argued that as the result of signalized intersections and lower travel speed constraints on state highways, the travel time as well as RUCs would increase. Also, RAC on the state highway was fourth that of the interstate highway seeing that heavy vehicle would remain longer on a pavement section which would result in rapid pavement deterioration. In 2015, The RealCost Software was employed to compute costs incurred on users over work zones [Kim et al. 2015]. The costs were calculated using RealCost analytical models. The reliable data bank as well as calculation techniques were provided to release the most accurate results. In 2016, a scenario-base model based on static traffic assignment was developed to assess the effects of five bridges closure on RUC due to M&R activities [Twumasi-Boakye and Sobanjo, 2016]. Cube Voyager Software calculated RUCs taking into account delay costs and VOCs. Results indicated that there was the increase of 20% to 60% in RUCs with respect to the bridge location.

According to the conducted literature review, the importance of homogeneous sections in RACs and RUCs calculation has not been investigated. Besides, the relationship between various traffic characteristics of roadways and RUCs, has not been carried out efficiently. Hence, the research was conducted by considering the research gaps to evaluate and estimate RUCs in Iran. RUCs accurate estimation would result in the best balance between construction costs and RUCs. The paper presented a localized and up-to-date database for RUC calculation utilizing the accessible software and analytical approaches.

3. Research Methodology

In order to determine and compare costs incurred on road users and agencies, the first step was to collect data regarding Pavement Condition Index (PCI), International Roughness Index (IRI) and central deflection (D_0) of Falling Weight Deflectometer (FWD) device on the selected roads network. These indices are the representatives of pavement deteriorations, pavement smoothness and structural capacity of sub-layers, respectively.

To collect the distresses on the selected road network, the procedure presented in ASTMD6433 was used. According to the standard, the area of 230±90 square meter has been specified for a sample unit. Hence, the length of 50-meter (first lane on one side of the two-lane highway) was used for pavements' condition monitoring. A total number of sample units were calculated dividing the highway length to the determined length of each unit, and a minimum number of sample units were used to collect different deteriorations [ASTMD6433, 2011]. PCI values were determined using Micropaver Software, Version 5.2. IRI was collected by Road Surface Profiler (RSP) mounted on special vehicles along the first lane. The device is installed on a special vehicle to measure pavement roughness in terms of the meter per kilometer using seven lasers on the RSP device [Arhin, Noel and Ribbiso, 2015]. In addition to these, using ASTMS D4694, central deflections under the loading plate of FWD testing device were collected under the applied tension of 900 kPa every 400 meters on the first lane on one side of the two-lane highway. The collected (D_0) data indicate the layers' stiffness more accurately [ASTMS D4694, 2015].

Homogeneous sections, where the variations attributed to above-mentioned criteria (i.e. PCI, IRI and D_0) are constant were determined using Cumulative Difference Approach (CDA) [Cafiso and Graziano, 2012]. Using the CDA, the average values of pavement performance indicators on a roadway are reduced from each collected data. Then, by performing cumulative summation on the calculated values and drawing the results; where algebraic signs changed can be considered as the borders of homogenous sections (i.e. initial homogenous sections). To be more precise, homogeneous sections are where the variations of any parameter are constant with respect to the calculated mean value. Hence, the initial homogenous sections were created based on each criterion. Consequently, the final homogenous sections, where IRI, PCI and D_0 are varied constantly were generated by combing the borders of initials ones. The next stage was to select the appropriate M&R alternative considering entire homogenous sections along with their functional and structural weaknesses. In addition to this, all the required data related to transportation fleet were gathered. The following sections explain different steps of data collection and costs analysis procedures.

3.1 Selection of Maintenance and Rehabilitation Treatments

Creating initial homogeneous ections based on PCI, IRI and D_0, the research was continued incorporating the initial segments into final homogenous ones. In any homogenous unit, indices followed the identical trend in the aspect of their variation. Figure 1 illustrates the geographical position of each road network in South Khorasan Province with their lengths and selected road numbers. In addition, Table 1 introduces the surface (i.e. PCI and IRI) and structural characteristics (i.e. the effective structural number (SN_{eff}), the required structural number (SN_{req}) and the overlay thickness) on selected roadways for each homogenous section.

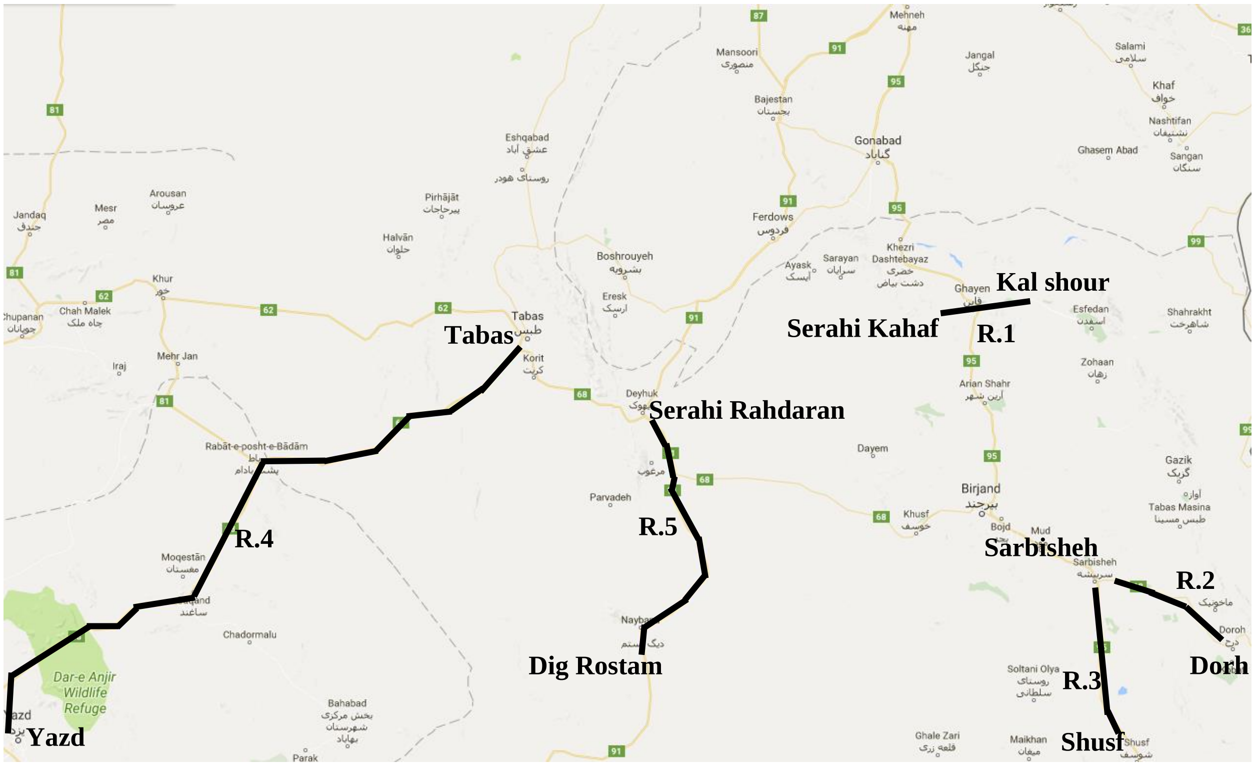

Figure 1. The selected roads network

Table 1. The characteristics of final homogenous sections

The Roadway number	Kilometrage (Km)	PCI	IRI (m/Km)	D_0 (Micron)	(SN_{eff})	(SN_{req})	Overlay thickness (Cm)
R.1	0 - 8	96	2	537	3.8	4.4	4
	8 –11.4	35	3.9	537	2.9	4.4	9
	11.4 – 21.4	35	3.9	816	2.1	4.6	14
	21.4 - 24	81	1.9	816	2.2	5	16
	24 – 40.7	81	1.9	578	2.9	4.6	10
R.2	0 – 26.7	82	1.85	709	2.8	4.7	7
	26.7 – 27.5	75	1.85	709	2.8	3.7	5
	27.5 – 28.3	75	3.67	709	2.5	3.5	8
	28.3 - 32	75	3.67	512	2.8	3.6	5
	32 – 39.8	76	3.67	512	2.4	3.2	5
	39.8 – 46.4	85	3.67	512	3.5	2.8	0
	46.4 – 49.4	83	3.67	512	3.2	2.9	0

(continued)	49.4 – 60.1	83	3.67	662	2.6	3.1	4
	60.1 – 65.9	64	3.67	662	3.7	3.1	3
	65.9 - 67	77	2.57	662	2.7	3	2
	67 – 71.4	77	2.57	662	3.3	3.3	1
	71.4 – 78.4	77	2.57	507	3.6	3.1	0
R.3	0 - 17	30	4.86	432	3.2	3.7	4
	17 - 28	93	2.5	432	3.4	3.8	3
	28 – 33.4	65	2.5	432	3.5	4.2	5
	33.4 - 35	19	2.5	432	3	4	6
	35 – 37.4	19	4.16	432	2.9	3.7	4
	37.4 – 58.8	19	4.16	701	2.7	4.3	9
	58.8 - 60	55	2.61	701	3.2	4.1	6
	60 - 77	55	2.61	424	3.8	4.2	0
	77 – 88.3	55	2.61	527	3.1	4.3	7
R.4	0 – 3.9	43	2.56	393	3.5	2.6	0
	3.9 – 6.1	62	2.56	393	3.1	2.7	0
	6.1 – 19.2	19	2.56	393	2.4	3.4	6
	19.2 – 24.3	87	2.56	393	2.4	3.1	4
	24.3 - 35	31	2.56	393	2.5	3	3
	35 - 38	28	2.56	393	2.6	2.9	3
	38 – 43.5	28	3.27	393	2.4	3	4
	43.5 – 48.5	28	3.27	555	2.2	3.4	7
	48.5 - 62	60	3.27	555	2.3	3.2	5
	62 - 70	38	3.27	555	2.5	3.4	6
	70 – 71.7	38	3.27	398	2.7	2.9	2
	71.7 - 78	74	3.27	398	2.8	2.7	2
	78 – 83.5	52	3.27	398	2.5	3	3
	83.5 - 89.2	52	3.27	502	2.2	3.6	7
	89.2 - 98	61	3.27	502	2.2	3.2	6
	98 - 111	61	2.52	502	2.4	3.1	4
	111 - 146	61	2.52	619	2.4	3.4	6
R.5	0 - 12	44	2.46	631	2.6	4.6	11
	12 – 12.8	44	3.86	631	2.5	5.2	15
	12.8 - 26	18	3.86	631	2.4	4.3	11
	26 - 36	18	3.86	495	2.8	4.3	9
	36 – 49.4	67	2.57	374	2.8	3.5	5
	49.4 - 73.8	67	2.57	472	2.8	4.3	9
	73.8 – 76.1	67	2.57	528	3.3	3	0
	76.1 - 78	27	2.57	528	3	3.6	4
	78 – 104.6	27	4.51	528	3.4	3.7	3

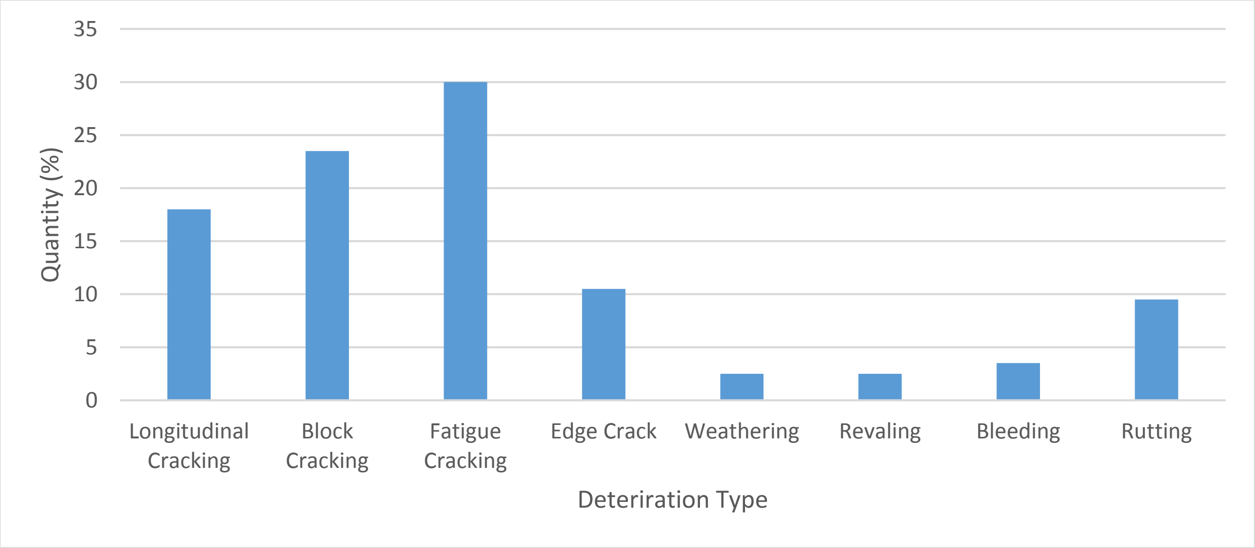

Figure 2. Different types of distresses and their percentage (Network-level)

With respect to characteristics of the roads network, PCI and IRI values varied from 18 to 96, and 1.85 to 4.86 (Km.m), respectively. Moreover, the central deflections derived from the applied tension of 900 kPa by FWD testing device, were lower than 1000 Micron (Between 374 to 816 Micron) in various sections. Figure 2 demonstrates the percentage of various types of collected distresses on the roads network using ASTMD6433 explained in section 3. collected during pavement condition surveying. Using back calculation, SN_{eff} , SN_{req} and the required asphalt overlay were calculated as well [Iran Highway Asphalt Paving Code No. 234].

With regard to the type and quantity of collected deteriorations, pavement smoothness and its structural attributes (i.e. overlay thickness), Table 2 demonstrates the proposed M&R alternatives. A suggested base alternative is a minimum maintenance project, performed on roadways on a regular basis (i.e., annually). The IRI value of 4.5 m.Km was chosen as a trigger value for implementation of rehabilitation activities, and IRI value of 2.85 m.Km was selected as a threshold value of preventive maintenance initiation [Fakhri, 2010]. Any segment where selected threshold values were reached would be considered as a candidate for M&R implementation during the analysis period.

3.2 Analysis Period

Analysis period is a planning time-span in which cost streams relevant to initial construction costs as well as future M&R costs are evaluated. The length of any analysis period must be long enough to include a pavement rehabilitation project [Caltrans, 2013]. In this study, the analysis period was assumed 10 years.

3.3 Traffic Data

Traffic data includes Annual Average Daily Traffic (AADT), traffic composition and annual growth rates. Owing to the network-level analysis, the annual growth rates in the 10 years' analysis period were assumed 3 and 5 percent for heavy and light vehicles, respectively. Tables 3 demonstrates AADT in the first year of the analysis period (2016) and calculated a total number of Equivalent Single Axle Loads (ESALs) during the analysis time-span (2016-2025). In addition to this, Table 4 illustrates traffic composition with respect to collected AADT [rmot.ir].

3.4 Discount Rate

Time has a value, and a value of money, spent in the future is lower than its current worth. Road projects consist of future M&R activities associated with related costs.

Table 2. The proposed M&R alternatives

Alternative	Work items
Base Alternative	Annual patching and crack sealing
Rehabilitation 1	HMA Overlay (8 Cm). Slurry seal. Crack sealing. Reconstruction
Rehabilitation 2	Cold milling (10 Cm) followed by an Overlay (10 Cm). HMA thin Overlay (4 Cm). Reconstruction

Table 3. Traffic data of a road network [rmto.ir]

The highway number	R.1	R.2	R.3	R.4	R.5
AADT	4,326	9,65	2,190	1,352	1,150
A total number of ESALs passing design lane	14,321,684	2,761,830	5,448,107	6,072,001	14,392,954

Table 4. The traffic composition [rmto.ir]

The highway number	R.1	R.2	R.3	R.4	R.5
Passenger car	56%	57%	60%	46%	22%
Truck	14%	14%	15%	11%	6%
Mini Bus	2%	3%	2%	3%	3%
Bus	6%	4%	6%	7%	6%
Two- axle light vehicles	6%	12%	7%	14%	18%
Two-axle heavy vehicles	2%	3%	2%	5%	18%
Three-axles	4%	6%	5%	11%	10%
Four-axle and more	4%	1%	3%	3%	17%

LCCA performs discounting method using a particular value of discount rate to demonstrate the time value of money.A discount rate is the function of two parameters; namely, inflation and interest rates. An interest rate is the benefit, assigned to a borrowed money, indicating the value added as time passes. The discount rate (i_{dis}) is calculated using Equation (1) [Caltrans, 2013].

$$i_{dis} = \frac{1+i_{int}}{1+i_{inf}} - 1 \qquad (1)$$

Where, i_{int} and i_{inf} are interest and inflation rates, respectively. If the interest rate were larger than the inflation, the discount rate would be the difference between parameters (Equation (2)) [Caltrans, 2013].

$$i_{dis} = i_{int} - i_{inf} \qquad (2)$$

Several research studies have been carried out concerning determination of actual discount rates. The range between 3 to 5 percent was proposed as the appropriate discount rate in United States of America. [Caltrans, 2013]. Reported values of interest rates in relevant studies conducted in Iran were far lower than published values by Iran Comprehensive Studies and relevant research works [Amini, 2014 and Egis and Metra consulting engineers, 2005]. Different percentages of 2.23, 5.52, -2.24 and -4.88 were reported taking into account various scenarios. In this study, according to Equation (2) and reported values, the negative amount of discount rate was chosen for LCCA. Owing to the HDM-4 inability to perform discounting procedure by negative rates, it was decided to choose zero as the actual discount rate.

3.5 Costs Estimation

As it was mentioned earlier, costs in the LCCA as well as the HDM-4 are divided into two parts; namely, RACs and RUCs. In the following parts, the relevant concepts and details are described.

3.5.1 Road Agency Costs Calculation

RACs include initial construction costs followed by future M&R expenditures that road agencies incur. RACs can be calculated by estimation of M&R projects' quantity multiplied by work items' unit costs. In doing so, HDM-4 is able to predict the pavement performance during the analysis period with respect to traffic data and IRI variation as time passes. Unit costs were calculated using National List Price. Table 5 provides unit costs correspond to proposed M&R treatments [List price, 2016]. Unit costs were estimated taking into account haul distance and overhead costs as well as site equipment, contract and regional coefficients.

3.5.2 Road User Costs Calculation

Generally, RUC calculation includes the estimation of monetary and non-monetary (e.g. environmental parameters) effects [Zhu, 2008]. With regard to the scope of the research, monetary impacts consist of value of time (or TTCs) and VOCs during M&R implementation projects. Repeated cycles of speed changes (i.e., acceleration and deceleration in traffic congestion) over work zones lead to increase in fuel consumption and other related operational features of vehicles. In addition to this, lower speed over work zones results in waste of users' time [Qin and Cultler, 2013]. The annual RUC is derived by Equation (3), where index j is the investment option [Kerali, 2002].

$$RUC_j = VOC_j + TTC_j \qquad (3)$$

To calculate above-mentioned factors, various data and unit costs related to a transportation fleet passing through the selected roads network must be collected. In doing so, statistics published by Road Maintenance and Transportation Organization (RMTO) in recent years, were utilized [rmto.ir]. Listed in Table 6, HDM-4 calculates VOCs taking into account various expenditures; namely, fuel, oil and tire consumption, vehicle utilization, crew hour, labor hours, parts consumption and overheads

Table 5. Estimated unit costs [List price, 2016].

Work items	Cost (Rial.m^2)	Pre-maintenance costs	
Patching by milling (5 Cm) and in-place cold mix	190737	-	
Crack sealing	87218	-	
Overlay (8 Cm)	221017	Patching	190737
		Edge cracking repair	190737
Slurry seal	53524	-	
Cold milling by special machine (10 Cm) and overlay (10 Cm)	321668	-	
Overlay (8 Cm)	221017	Patching	190737
		Edge cracking repair	190737
Reconstruction	571801	-	

In addition, TTCs consist of costs associated with passenger delay time and cargo holding time [Archondo-Callao, 2010]. All these factors are computed using developed mathematical models in HDM-4 Software. The brief explanation of effective parameters and a number of mathematical models were provided, as follows;

The model used to determine the fuel consumption effects on users' costs relates the consumption prediction pattern to the total power requirements of the engine. The models are provided for uphill and downhill sections. To predict and model lubricating oil consumption, two parameters; namely, oil loss due to contamination and vehicle operation are taken into account. Equation (4) is used by the software to calculate the oil consumption for each vehicle type k, for each traffic period p [Kerali, 2002].

$$OIL_{kp} = OILCONT + OILOPER * FC_{kp} \tag{4}$$

Where, OIL_{kp} is oil consumption (1.1000 Km) for vehicle type k during traffic flow period p, $OILCONT$ oil loss due to contamination (1.1000 Km), $OILOPER$ oil loss due to operation (1.1000 Km), and FC_{kp} fuel consumption (1.1000 Km) for vehicle type k during traffic flow period p. $OILCONT$ is derived by dividing engine capacity (liters) to distance between oil changes (1000s Kilometers), and $OILOPER$ is a function of fuel consumption patterns. HDM-4 manual provides default values of above-mentioned parameters for each vehicle type.

The Tire consumption model is a function of lateral and normal forces on each wheel of a vehicle traveling over uphill and downhill segments. Vehicle utilization is defined by annual kilometrage driven over the annual working time. The working time excludes time spent on idling, eating, sleeping or resting from the total travel time. It only includes time spent on driving, loading, unloading and refueling. The annual kilometrage driven and annual working time were entered as constant values by a user [Kerali, 2002].

Crew hour modeling is achieved by the product of a number of crew hours and the crew salary. Equation (5) is used to model the parameter with respect to vehicle type, traffic flow and vehicle operating costs [Kerali, 2002].

$$CH_{kp} = \frac{1000 * (100 - PP_k)}{100 * SS_{kp}} \tag{5}$$

Where, CH_{kp} is a number of hours per crew members per 1000 veh-Km for vehicle type k during traffic flow period p, PP_k private-use percentage (i.e. when no passenger is on board exept the driver), and SS_{kp} vehicle operating speed (Km.h) during traffic flow period p. The annual average number of hours for each crew member per 1000 vehicle-kilometers is modeled using Equation (6) [Kerali, 2002].

$$CH_{kav} = \frac{\sum_{p=1}^{n} HRYR_p * HV_p * CH_{kp}}{\sum_{p=1}^{n} HRYR_p * HV_p} \tag{6}$$

Where, CH_{kav} is the average number of hours for each crew member per 1000 veh-km for vehicle type k, $HRYR_p$ the number of hours in traffic flow period p, HV_p the hourly traffic flow in period p as a proportion of AADT and CH_{kp} a number of hours for each crew member per 1000 veh-km.

In order to calculate maintenance labor hours, labor wage is introduced to the software by a user. Maintenance labor hours are modeled as the function of parts consumption as well as traffic flow periods. Parts consumption is modeled using spare parts costs, and calculated as a portion of the replacement vehicle price. It depends on vehicle age (in terms of Km), IRI values and acceleration-deceleration cycles. Overheads cover the entire costs regarding insurance, parking, and any overheads associated with the crew (for example, training, uniform and etc.). Overhead costs are measured as a function of the annual vehicle utilization and average operating speed using Equation (7) [Kerali, 2002].

$$OC_{kp} = \frac{1000 * OA_k * (100 - PP_k)}{100 * SS_{kp} * HRWK0_k} \tag{7}$$

Where, OC_{kp} is overhead cost per 1000 veh-km for vehicle type k during traffic flow period p, and OA_k overhead cost per year, for vehicle type k (input by the user). Also, $HRWK0_k$ is the average annual working time. Other parameters were defined before. The annual average overhead costs per 1000 vehicle-kilometers is modeled using Equation (8) [Kerali, 2002].

$$OC_{kav} = \frac{\sum_{p=1}^{n} HRYR_p * HV_p * OC_{kp}}{\sum_{p=1}^{n} HRYR_p * HV_p} \tag{8}$$

Where, OC_{kav} is annual average overhead costs per 1000 veh-km for vehicle type k and OC_{kp} is overhead costs per 1000 veh-km for vehicle type k during traffic flow period p. Other parameters were defined before.

In general, The users' costs over work zones depend on the length of highways, type of M&R projects, a number of blocked lanes, highway capacity and duration of lane closure. The models used to compute the TTCs in HDM-4 are functions of passenger travel time and cargo holding time. Passenger travel time is calculated using two affecting parameters; namely, working passenger-hours (passenger working time) and non-working passenger-hours (passenger non-working time). Working passenger-hours is the number of passenger-hours per 1000 vehicle-kilometers spent on travelling during working time (i.e. work-base trips), and non-working passenger-hours is the number of passenger-hours per 1000 vehicle-kilometers spent on other types of trips expect work-base trips. These parameters result in the analysis of delays along with M&R projects. The number of working and non-working passenger-hour are computed using Equations (9) and (10), respectively [Kerali, 2002].

$$PWH_{kp} = \frac{1000 * PAX_k * W_k}{100 * SS_{kp}} \tag{9}$$

$$PNH_{kp} = \frac{1000 * PAX_k * W_k}{100 * SS_{kp}} \tag{10}$$

Where, PWH_{kp} and PNH_{kp} are the number of working and non-working passenger-hours hours per 1000 veh-km, for vehicle type k during traffic flow period p, respectively. PAX_k is a number of passengers (non-crew occupants) in vehicle type k, and W_k percentage of passengers on work-purpose journey. SS_{kp} was introduced before. In addition to this, the annual average working and non-working passenger-hours can be derived by Equations (11) and (12), respectively [Kerali, 2002].

$$PWH_{kav} = \frac{\sum_{p=1}^{n} HRYR_p * HV_p * PWH_{kp}}{\sum_{p=1}^{n} HRYR_p * HV_p} \qquad (11)$$

$$PNH_{kav} = \frac{\sum_{p=1}^{n} HRYR_p * HV_p * PNH_{kp}}{\sum_{p=1}^{n} HRYR_p * HV_p} \qquad (12)$$

Where, PWH_{kav} and PNH_{kav} are annual average number of working and non-working passenger-hours per 1000 veh-km, for vehicle type k; respectively. Other parameters were defined earlier. Finally, cargo holding time known as the number of vehicle-hours spent in transit can be calculated by Equations (13) and (14) [Kerali, 2002].

$$CARGOH_{kp} = \frac{1000}{SS_{kp}} \qquad (13)$$

$$CARGOH_{avv} = \frac{\sum_{p=1}^{n} HRYR_p * HV_p * CARGOH_{kp}}{\sum_{p=1}^{n} HRYR_p * HV_p} \qquad (14)$$

Where, $CARGOH_{kp}$and $CARGOH_{avv}$ are annual number of cargo holding hours per 1000 veh-km, for vehicle type k during traffic flow period p and annual average number of cargo holding hours each 1000 veh-km, for vehicle type k, respectively. As stated before, the above-mentioned parameters are demonstrated in Table 6. To this end, HMD-4 was able to compute RACs and RUCs, resulted from M&R implementation projects using Tables 5 and 6.

4. Cost Analysis

In this paper, HDM-4 software was used to evaluate cost streams, resulted from implementation of different M&R methods during 10 years analysis period. Utilizing the determined discount rate for road projects, future costs were discounted to their present values for the purpose of the economic analysis. Towards this end, the summation of discounted costs on each homogeneous section was calculated to demonstrate costs incur on road agencies and users over each highway. Considering the premier objective of this study, in the following, a number of bar charts are provided, illustrating the comparison between RACs and RUCs while M&R alternatives were taken place on highways. As mentioned earlier, RUCs consist of VOCs and TTCs, demonstrated separately in the following figures.

According to Figure 3, owing to the implementation of the base alternative (Annual patching and crack sealing), RACs were far lower than RUCs. In all cases, RUCs were approximately 10 times higher than RACs.

Costs incurred on road users were the highest on R.4 roadway. Although the total number of ESALs in 10 years analysis period was estimated 6 million on R.4, RUCs were higher than R.1 and R.5 with the 14 million ESALs. It can be argued that in addition to traffic flow, other factors such as traffic composition, highway length and a number of repaired segments affect the RUCs, significantly. Moreover, VOCs were always higher than TTCs due to high cost associated with owning and operating vehicles in Iran.

Application of the base alternative to R.1 resulted in the lowest RACs compared to others. This can be attributed to the length of R.1 as well as the pavement condition being the shortest and the least deteriorated highway, respectively. On the contrary, R.4 was associated with the highest RACs which can be related to the highway length and the number of deteriorated homogenous sections being the greatest. Overall, when base alternative was performed for M&R purpose; R.4 had the highest RUCs and RACs, and R.1 indicated the lowest RUCs and RACs.

Table 6. Vehicle fleet information [rmto.ir]

Vehicle type	Passenger car	Truck	Mini Bus	Bus	Two- axle light vehicles	Two -axle heavy vehicles	Three-axles	Four-axle and more
The number of wheels	4	4	4	6	6	6	10	18
The number of axles	2	2	2	2	2	2	2	>4
Tire type	Radial	Radial	Radial	Bias	Bias	Bias	Bias	Bias
Annual kilometrage driven	23,000	30,000	30,000	70,000	40,000	40,000	86,000	86,000
Annual working hours	400	914	2,056	2,632	1,450	1,450	1,450	1,570
Private-Use percentage	75	50	25	25	0	0	0	0
The number of passengers	3	1	16	25	1	1	1	1
Work-Related passenger trip	25	50	75	75	100	100	100	100
ESAL factor	0.000442	0.00376	0.0358	0.304	1.737	6.603	4.71	6.92
The operating weight (Ton)	2	3	6	9	15	20	26	32
The new vehicle price (Million Rial)	300	184	628	2,066	2,734	3,348	1,080	4,000
New tire price (Rial)	1,420,000	1,760,000	2,900,000	11,000,000	11,000,000	11,000,000	2,500,000	8,100,000
Fuel price (Rial.per lit)	10,000	10,000	10,000	7,200	7,200	7,200	7,200	7,200
Lubricant price (Rial.per Lit)	73,000	7,3000	5,700	5,700	5,700	5,700	5,700	5,700
Maintenance labor costs (per hour)	91,750	91,750	91,750	137,500	137,500	137,500	137,500	137,500
Crew wages (per Hour)	0	0	68,000	400,000	96,000	120,000	137,000	135,000
Passenger working time (per hour)	109375	109375	109375	109375	109375	109375	109375	109375
Passenger non-working time (per Hour)	27344	27344	27344	27344	27344	27344	27344	27344
Cargo holding cost (Rial)	0	10000	0	0	20000	20000	20000	40000

With reference to Figure 4, in all cases, RUCs outnumbered RACs while Rehabilitation alternative (1) (including 8 Cm Overlay, Slurry seal, Crack sealing and Reconstruction) was implemented. As for RUCs, R.1 and R.4 were associated with the lowest and highest costs, respectively. This result is similar to outcomes obtained by Figure 3. This can be attributed to the 146 Km length of R.4 and sequence of M&R projects disturbing traffic flow in different years. Furthermore, RUCs on R.2 was the lowest, which may be related to short length of the highway. Also, VOCs were always higher than TTCs on highways which may be attributed to high costs coupled with vehicle operation during traffic congestion through work zones. Furthermore, with respect to Figure 4, it can be seen that, R.4 where the highest costs were incurred on users, was associated with highest RACs as well.

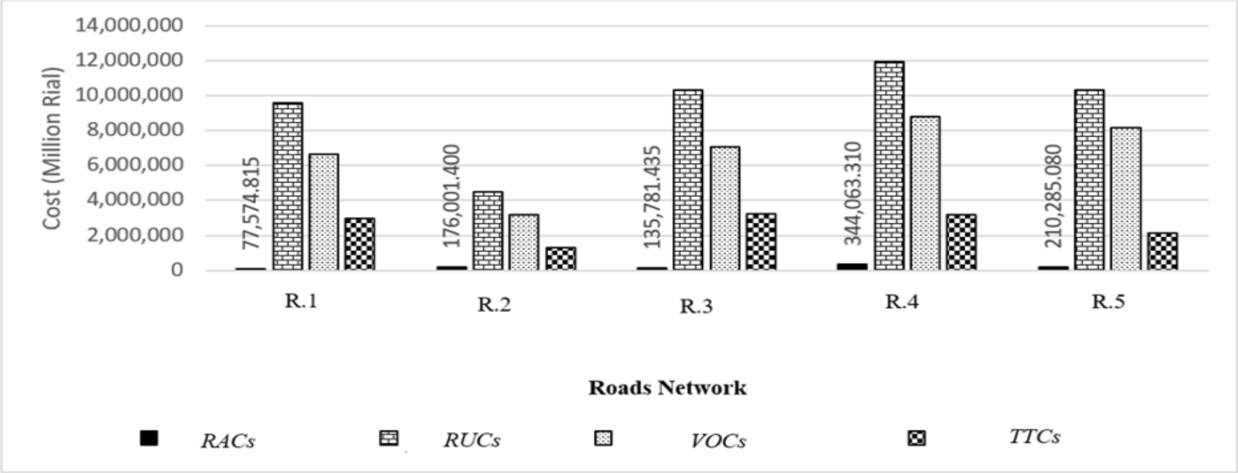

Figure 3. RACs and RUCs resulted from base alternative implementation during the analysis period

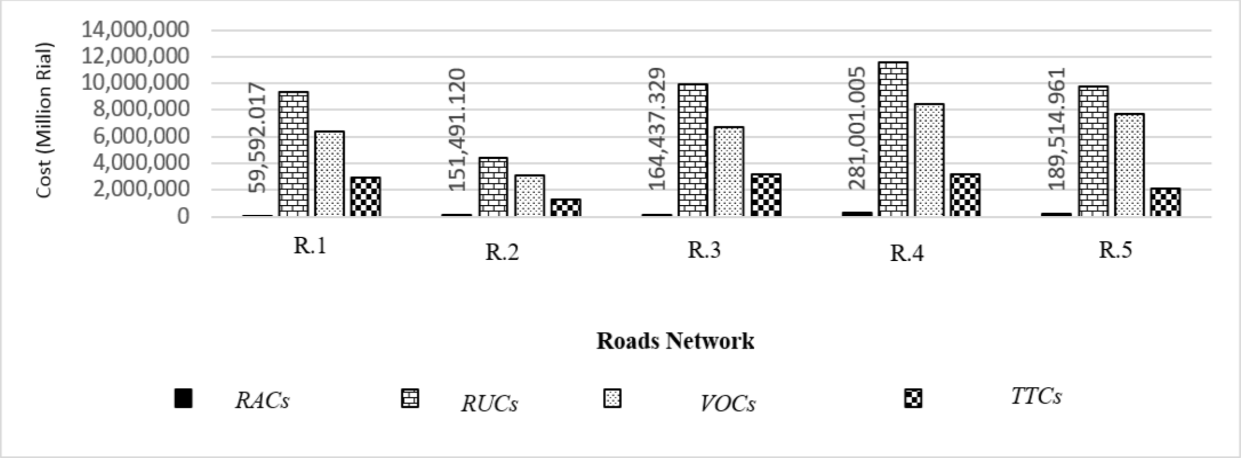

Figure 4. RACs and RUCs resulted from Rehabilitation alternative (1) implementation during the analysis period

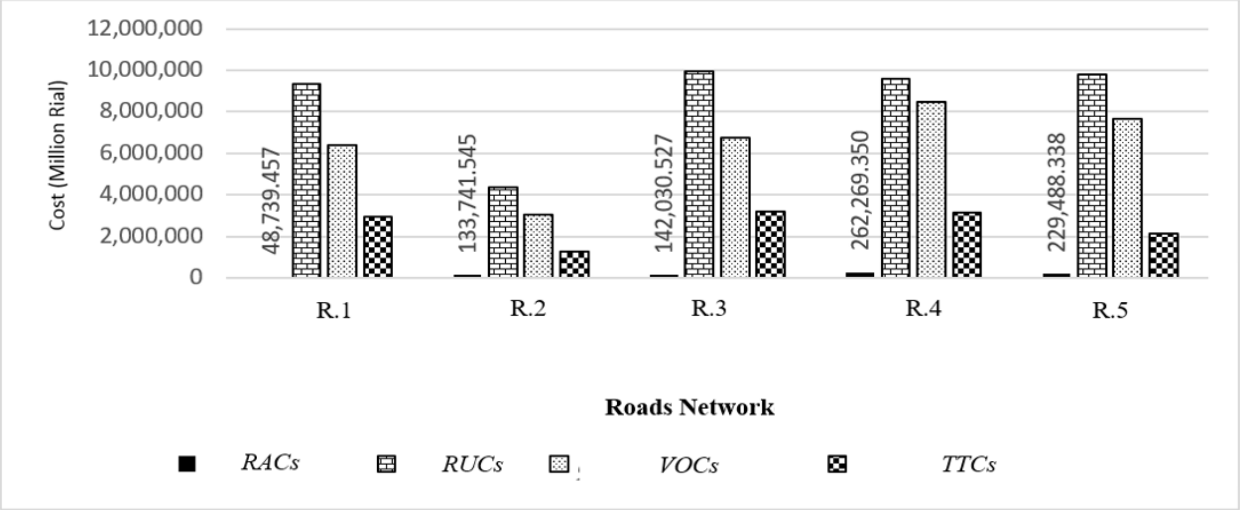

Fig. 5. RACs and RUCs resulted from Rehabilitation alternative (2) implementation during the analysis period

According to Figure 5, when the Rehabilitation alternative (2) (including Cold milling (10 Cm) followed by 10 Cm Overlay, Thin overly (4 Cm) and Reconstruction) was performed, the RUCs were higher than RACs. As for RUCs, R.2 had the lowest number of ESALs (approximately 3 million) in the analysis period, including the lowest road user cost as well. Although the length of R.2 was higher than R.1, owing to fewer total numbers of ESALs, costs users incurred were lower. It can be stated that, RUCs did not depend on road length, exclusively. Traffic composition, vehicle axle loads and sequence of M&R activities were also important factors, affecting RUCs. Furthermore, VOCs were higher than TTCs on the whole network, observed by Figures 3 and 4 as well. Regarding RACs, R.1 and R.4 had the lowest and highest costs; respectively, being identical to results obtained by Figures 3 and 4.

According to Figures 3 and 4, while other proposed M&R alternatives were taken place, R.4 was associated with the highest RUCs. However, based on Figure 5, implementation of Rehabilitation alternative (2) was associated with higher RUCs on R.3. The latter indicated that, RUCs did not follow a particular trend in different M&R scenarios. With regard to the outcomes illustrated by the provided bar charts, the RUCs and RACs were compared. Finally, the importance and complexity of RUCs calculation in the economic analysis was revealed.

Thus the RUC calculated by localized data using HDM-4 can be acceptable since the same results were achieved by previous research work [Meneses and Ferreira, 2010, Meneses and Ferreira, 2013, Gillespie and McGhee, 2007, Islam and Buttlar, 2012, Onyango et al. 2014] in which RUC played a crucial role in Decision-making procedure regarding selection of M&R options since RUC made up large proportion of costs.

5. Conclusion and Recommendation

The research was carried out to calculate road agencies and users costs because of implementation of various M&R operations. The main objective of the paper was to reveal the importance of RUCs along with their effects on the economic analysis of pavement preservation projects. Utilizing HDM-4 Software, the RACs as well as RUCs were computed. To this end, required localized input data were collected. Models were calibrated using the provided database. The outcomes confirmed the ability of HDM-4 to calculate RACs and RUCs, properly. The results can be outlined as follows,

1. The first point to note is that, RUCs were remarkably higher than RACs with respect to proposed M&R programs. The latter provided a concrete evidence regarding the importance of RUCs calculation in any step of M&R treatment and planning. The latter also confirmed the outcomes achieved by previous research works in which higher weight of RUCs than RACs was revealed in decision-making procedures.
2. Research outcomes indicated that, in the case of selected roads network, RUCs were approximately 10 times higher than RACs.
3. Results demonstrated that, the implementation of base alternative was along with the highest RUCs compared to other M&R alternatives. This can be due to its annual implementation and repetitive disturbance in traffic flow.
4. It was concluded that RAC could be only related to highway length, M&R unit costs and sequence of M&R operations. However, apart from road length and traffic volume, factors such as traffic composition and the number of ESALs over the analysis period are of the most influential parameters in RUCs calculation. That is to say, RUCs vary with respect to M&R scenarios, and did not follow the identical trend. This justified the need to consider RUCs in economic analysis.
5. Finally yet importantly, VOCs were always higher that TTCs which can be attributed to the high costs of owning and operating vehicles in Iran.

With respect to the importance of RUC calculation in determination of the most cost-effective and appropriate M&R treatments, further research projects must be conducted to obtain more reliable results. RUCs consist of other parameters; namely, accidents cost and environmental costs. Hence, carrying out research works regarding incorporating these parameters into RUC calculation would result in more accurate outcome. In addition using other types of software such as RUCKS can be taken into account to compute RUC and compare the results with the findings presented in this research.

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