Development of a Sustainable Maintenance Strategy for Forest Road Wearing Course in Different Climate Zones

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Research Article

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Abstract

In the recent decade, forest roads with a gravel surface course constructed in the different climates of Hyrcanian zone have worn out due to maintenance problems. This study was done to investigate the effect of traffic, maintenance budget, and climate on deterioration of forest roads and determine the best time and type of maintenance activities in the Mediterranean, sub-humid and semi arid climates. Unmanned aerial vehicle (UAV) was used to monitoring Unpaved Road Condition Index (UPCI), immediately after maintenance activities and each season for one year. Moreover, deterioration time of the wearing course was predicted using *Monte Carlo time series analysis in MATLAB*. Results showed that sub-humid climate presented lower UPCI (7.19) compared to the two other climates. UPCI values for Mediterranean and semi-arid climates were 7.81 and 8.82, respectively. In most cases, where roads were maintained by high-budget strategy, deterioration time was longer than other strategies, but cost-effectiveness (CE) value of low-budget strategy was more than other strategies in all traffic levels of Mediterranean climate and high-traffic roads in semi-arid climate. Low-budget maintenance activities include one culvert improvement per 6 km, light blading, 30 mm layer gravelling. In semi-arid climate, medium-budget maintenance strategy was more efficient in medium and low-traffic roads. In, sub-humid climates it was detected that CE values severely vary depending on the level of traffic. Medium, high and low budget maintenance strategies were respectively efficient in high, medium and low-traffic roads. High budget maintenance activities include one culvert improvement per 4 km, heavy blading and local compaction, 60 mm layer gravelling. Overall, it was concluded that monitoring UPCI over time and probability analysis using time series is useful for sustainable and long term management of forest roads.

Introduction

Forest roads play an important role in forest management, wood and non-wood products gathering, recreation, hunting, etc. During the last decade, considerable efforts have been made to prevent forest harvesting, especially in developing countries. These attempts have led to a decrease of forestry plan incomes and road sector investments (Hrůza et al. 2018; Akay et al. 2020; Fraefel et al. 2021). Forest roads with a gravel surface course constructed in the different climates have worn out due to maintenance budget problems. So, it is necessary to find a sustainable, cost-effective strategy to maintain forest road wearing course over time because degradation on the wearing course has an essential influence on traffic safety and forest accessibility (Ferenčík et al. 2019; Akay et al. 2021). A method to controlling road maintenance costs is to obtain and update timely information on the road surface conditions. Sustainable forest road maintenance can be defined as all activities, including regular maintenance tasks, blading, reshaping, spot graveling, and other tasks that provide and maintain road surfaces at an adequate level of service for the long term (Chamorro Giné and Tighe 2009; Yurtseven et al. 2019; Akgul et al. 2019).

In the Hyrcanian forests, the mean average funding level for the support travel system and road maintenance per year was 433 $, with a range from 400$ to 470$, with an overall decreasing trend. Most the forest roads in this region are gravel roads. Gravel roads consist of a layer of mountainous and/or river materials constructed based on specified standards and provide a passable all-weather surface. A standard gravel forest road consists of 40–80% gravel, 20–60% sand, and 8–15% fine particles (Gotosa et al. 2015; Parsakhoo et al. 2021). Corrugations, potholes, erosion, rutting, dustiness or presence of fine material, exposed oversized aggregates, gravel loss, crown and roughness defects, poor cross-fall and profile are the common problems that can be observed on surfaces of gravel forest roads (Setyawan et al. 2015; Yoshida et al. 2016; Qiao et al. 2020). Recent studies have evaluated the different management tools to find a cost-effective and effective strategy for road maintenance. In Iran, the Genetic Algorithm was evaluated by Heidari et al. (2018) to identify the warning level of the road wearing course and provide a plan for the maintenance of the forest road network over five years. Goudarzi and Najafi (2018) showed that the Analytical Hierarchical Process (AHP) can prioritize the forest road maintenance from different spatial and temporal points of view using the generated model according to expert knowledge and effectiveness these factors.

Models were developed from the probabilistic analysis of field assessments and calibrated with Markov chains and Monte Carlo for simulating wearing course deterioration over time. One of the advantages of this technique is that it can be used by forest engineers with scarce technical resources and historical data (Osorio-Lird et al. 2018). Monte Carlo analysis of Unpaved Road Condition Index (UPCI) is one of the most effective tools for risk analysis. The primary purpose of Monte Carlo analysis is to predict wearing course condition and the life cycle cost for determining the suitable time table (Pazhouhan et al. 2020). Unpaved roads condition performance depends on the sub-based materials, climate condition, wearing course thickness, road age, traffic volume, the strength of surfacing materials. Severe climate, traffic, or poor structural strength increases the failure probability of road wearing course (Aruga et al. 2022).

The timely and proper maintenance of forest roads is essential for sustainable serviceability of roads, and an effective method to detect road surface problems is Unmanned Aerial Vehicles (UAV) (Tan and Li 2019). UAV's are considered useful tools for acquiring reliable information about the surface of the forest road (Dadrasjavan et al. 2019). Ruzgienė et al. (2015) showed that the correctness of the digital surface model for roads generally depends on camera resolution, flight height, and accuracy of ground control points. Determining road maintenance type and cycle is one of forest engineer's issues and challenges (Grajewski 2016). Moreover, estimating probable time and the project budget is still unpredictable to managers due to the traditional project control.

In this study, we tried to present a method for considering the probability of road deterioration by given time and cost in a forest. Monte Carlo is one of the most effective tools in risk prediction and analysis based on random numbers. Road maintenance tools commonly require detailed road condition data, comprehensive field evaluations, complex processes for model calibration, and long-term perspective. It can be stated that there is no sustainable maintenance program currently available in Hyrcanian forests that can overcome the four problems described above. The objectives of this research were to: (1) Investigate the effect of traffic levels, maintenance budget levels, and climate conditions on the deterioration of forest roads, (2) Determine the best time of maintenance activities based on probability analysis and UPCI methodology and (3) Determine the proper maintenance and repairing activities to slow road deterioration.

Material And Methods

Description of the study area

The study was conducted in three different climate zones within the Hyrcanian forests in the north of Iran (Fig. 1). These forests stretch 850 km along the southern coast of the Caspian Sea in the temperate broadleaf and mixed forest biome. In these regions, the road network is used by forestry machinery and public transport on holidays. This traffic can increase the damage to unpaved roads. General characteristics of study areas have been illustrated in Table 1:

Case studies inventory and field data

In this study UAV was used to monitoring unpaved road conditions based on UPCI (Chamorro Giné and Tighe 2019). These involve a RGB camera of 12 Megapixel to quantify the extent and severity of road problems observed on road sample units. We found three traffic levels and three maintenance budget levels in each climate zones of Mediterranean, sub-humid and semi-arid. In each climate, 18 sample unites each of with a length of 500 meter were randomly selected on road network. Totally 54 sample units and 27 km road were monitored in this study. Evaluations were made immediately after each seasons for one year to capture the effects of climate over the road surface. Totally 27 km of roads were surveyed in three climates. UPCI was estimated using Eq. 1:

UPCI = 10–1.16CR − 2.25PT − 1.47ER − 0.33RT – 1.56OA – 1.58CW (1)

Where CR is corrugations evaluated as the mean vertical distance between the highest and lowest point of the three consecutive deformations in centimeters, PT is potholes measured as the product of the mean diameter in meters, depth in meters and number of potholes in a sample unit. ER or erosion is a nominal variable considered as 1 if either erosion depth is greater than 5 cm or width is greater than 10 cm. RT is rutting evaluated as the mean vertical distance between the highest and lowest point of a rut obtained from three measures per wheel path in cm. OA or exposed oversized aggregate is a nominal variable, considered as 1 if oversized aggregate with mean diameters greater or equal to 5 cm and CW or crown condition is a nominal variable considered as 0 if crow have good condition, 0.5 in fair condition and 1 in poor condition (Chamorro Giné and Tighe 2019).

Road defect analysis

The road wearing course defects was detected with the use of UAV. The UAV used for the research work is a Rotary wing UAV which consist of four motors and is called a Quadcopter. It can be controlled either by autonomous mode or manual mode. The total duration taken to fly the UAV is 30 minutes and at an altitude of 60m. Collected images were processed using Agisoft Metashape software (Fig. 2). After the image processing, from the filled and closed image, the wearing course distress (in pixels) in order to do the severity analysis (Saha and Ksaibati 2017). Support vector machine (SVM) in eCognition software was used to classify different road defects (Fig. 3). The classification process was carried out with decision trees. The depth and surface of defects were measured in ArcGIS 10.1 (Bicici and Zeybek 2020).

Classification of traffic and budget levels

Most of the road wearing course deterioration caused by traffic is related to the traffic volume. In this study, low and moderate volume traffic gravel roads commonly present less than 10 and 10–20 vehicles per day. In addition, traffic volumes higher than 20 vehicles per day were classified as high traffic (Table 3). Three budget levels were considered in the definition of maintenance strategies: Low, Medium, and High. Budget levels and related maintenance activities are presented in Table 4.

Cost-effectiveness analysis

In this study Effectiveness (E) of different maintenance strategy was estimated using Eq. 2:

E =$\sum_{1}^{UPCI_T \geq UPCI_M} (UPCI_T - UPCI_M) - (\sum_{UPCI_M \geq UPCI_N}^{1} UPCI_M - UPCI_N) \times AADT \times LS$ (2)

Where $UPCI_T$ is UPCI after yearly maintenance until UPCI minimum is reached, UPCIM is minimum acceptable UPCI, $UPCI_N$ is yearly UPCI from the needs year to the maintenance year, AADT is annual average daily traffic and LS is road length. The Unit Effectiveness (UE) for a semi-annual cycle of 10 year analysis period was calculated using Eq. 3:

UE = $\sum_{n=1}^{40} \left(\frac{UPCI_B + UPCI_A}{2}\right) - 4 \times 40$ (3)

Where $UPCI_B$ is UPCI before applying maintenance strategy and UPCIA is UPCI immediately after applying maintenance strategy. Cost Effectiveness (CE) of each strategy was calculated following Eq. 4:

CE= $\frac{E}{PWC}$ (4)

Where PWC is present worth of maintenance costs. The maintenance cost range for low, medium and high budget strategies in Hyrcanian forests were 110–125$ km^{-1}, 185–230 S km^{-1} and 281–333 $ km^{-1}, respectively.

Statistical analysis

Experiment factorials were defined in this study. This factorial including UPCI as a dependent variable and climate, traffic and maintenance budget levels as independent variables was designed in SPSS Statistics version 23 software (Fig. 4). MATLAB software was used to predict deterioration time of the wearing course of different forest roads using Monte Carlo time series.

Results

Analysis of variance for the effects of independent variables on UPCI

Results indicated that UPCI was significantly different among semi-arid, sub-humid and Mediterranean climates ($P < 0.01$). Road maintenance strategy with varying levels of budget had a significant effect on UPCI values, as a lower UPCI was observed for low budget maintenance roads ($P < 0.01$). Results indicated that traffic levels or severity on forest roads could significantly change the UPCI ($P < 0.01$). There were no significant interaction effects from the mentioned independent parameters on UPCI ($P > 0.05$), except for climate and traffic ($P < 0.05$; Table 6).

Effect of maintenance strategies with different budget levels on UPCI

Figure 5 presents a comparison among the mean condition of roads in different road maintenance strategies in Mediterranean, semi-arid and sub-humid climates. In all studied climate zones, UPCI values for roads were maintained with a low budget standard was significantly lower than two other budget classes ($P < 0.05$). For roads were maintained with a high budget in Mediterranean climate, the road in initial condition presented a mean UPCI of 9.16 and after one year a mean UPCI of 7.74 (annual deterioration 15.5%). Annual deterioration rate of forest roads in semi-arid and sub-humid climates were 15.6% and 23.9%, respectively. For roads were maintained with a medium budget in Mediterranean climate, the road in initial condition presented a mean UPCI of 8.79 and after one year a mean UPCI of 6.91 (annual deterioration 21.4%). Deterioration rate of forest roads in semi-arid and sub-humid climates were 14.1% and 26.4%, respectively. For roads were maintained with a low budget in Mediterranean climate, the road in initial condition presented a mean UPCI of 8.32 and after one year a mean UPCI of 6.54 (annual deterioration 21.4%). Deterioration rate of roads in semi-arid and sub-humid climates were 29.7% and 24.8%, respectively.

Effect of traffic levels and climate on UPCI

Figure 6 presents a comparison among the mean condition of roads in different traffic levels in Mediterranean, semi-arid and sub-humid climates. In all studied climate zones, UPCI values for roads with a low traffic was significantly higher than two other traffic levels ($P < 0.05$). For forest roads with a high-traffic volume in Mediterranean climate, the road in initial condition presented a mean UPCI of 8.3 and after one year a mean UPCI of 5.9 (annual deterioration 29.3%). Annual deterioration rate of forest roads in semi-arid and sub-humid climates were 19.8% and 31.0%, respectively. For roads with a medium-traffic volume in Mediterranean climate, the road in initial condition presented a mean UPCI of 8.7 and after one year a mean UPCI of 7.1 (annual deterioration 16.0%). Deterioration rate of forest roads in semi-arid and sub-humid climates were 18.6% and 20.2%, respectively. For roads with a low-traffic volume in Mediterranean climate, the road in initial condition presented a mean UPCI of 9.2 and after one year a mean UPCI of 8.2 (annual deterioration 10.9%). Deterioration rate of roads in semi-arid and sub-humid climates were 20.2% and 21.0%, respectively (Fig. 6). From the analysis of mean data it is observed that important difference exists among climates. Sub-humid climate significantly presented lower UPCI (7.19) compared to the two other climates. UPCI values for Mediterranean and semi-arid climates were 7.81 and 8.82, respectively (Fig. 7).

Analysis road condition performance curves

The road surface performance curves obtained from the simulation of time series for roads with different maintenance strategy and traffic levels are presented in Figs. 8. Each graph includes three curves, representing the performance observed under semi-arid, Mediterranean and sub-humid climates. In high traffic roads in semi-arid climate the UPCI curves shows same trend for all maintenance strategy (Fig. 8a) It is observed that, the mean UPCI decreased rapidly during one year in semi-arid climate, especially in high-traffic roads maintained by low budget level. The UPCI performance of medium and low-budget strategy were same in medium (Fig. 8b) and low traffic roads (Fig. 8c). In Mediterranean climate, similar trend is observed for different maintenance strategy for roads in each traffic levels of high (Fig. 8d), medium (Fig. 8e) and low (Fig. 8f). As expected for sub-humid climate, the UPCI value drops significantly during the first year of service especially in high-traffic roads due to the appearance of distresses caused by traffic and climate (Fig. 8g). High budget maintenance strategy in medium traffic roads can increase the service life of the road (Fig. 8h), while the UPCI performance of different maintenance strategy in low-traffic roads is same (Fig. 8i). In the last three to five years of service, a wearing course of road presents severe access problems and is in poor and very poor condition, resulting in UPCI values less than 4.

Determining time to deterioration and maintenance cycle

In Mediterranean climate where high and medium-traffic roads were maintained by high-budget strategy, deterioration time was longer than other maintenance strategies and number of maintenance per decade was lower, while in low-traffic roads, number of maintenance per decade after low-budget maintenance activities was more than those of other strategies. In semi-arid climate where high traffic roads were maintained by low-budget strategy, deterioration time was longer than other maintenance strategies and number of maintenance per decade was lower. In low and medium-traffic roads, maintenance cycle after high-budget maintenance activities was longer compared to the other strategies. In sub-humid climate, where high, medium and low-traffic roads were maintained by high-budget strategy, deterioration time was longer than other maintenance strategies and number of maintenance per decade was lower (Table 6).

Determining the cost-effectiveness of different maintenance strategies

The cost-effectiveness analysis evaluates the effects of maintenance strategy during the whole life cycle of a road. From this analysis, optimal maintenance strategy was defined for each traffic levels in different climate zones. In Mediterranean climate zone it was observed that CE values of low-budget maintenance strategy was more than other strategies in all traffic levels. In semi-arid climate zone, CE values of low-budget maintenance strategy were more than those of other strategies only in high-traffic roads. In medium and low-traffic roads, medium-budget maintenance strategy was more efficient based on CE analysis. In, sub-humid climate, CE values severely vary depending on the level of traffic. Medium, high and low-budget maintenance strategies were respectively efficient in high, medium and low-traffic roads based on CE values (Table 7).

Discussion

Road defects appear in corrugations, potholes, rutting, and erosion because of deterioration (Maeda et al. 2018). To this end, various maintenance strategies with different budget levels have been developed to repair road damage rapidly and improve UPCI (Akay 2006; Aruga et al. 2022). In present study, although the three study sites are within the same biome, there is significant variation in their climates. We found that forest roads deteriorate over time due to the combined effects of traffic and climate. From the analysis, the medium and high-budget maintenance road presents in a good condition between first and second analysis years because of an extensive maintenance and reconstruction process. Annual deterioration of roads maintained by high budget in Mediterranean, semi-arid and sub-humid climates were 15.5%, 15.6% and 23.9%, respectively. In addition, these values for roads maintained by low-budget strategy were 21.4%, 29.7% and 24.8% in Mediterranean, semi-arid and sub-humid climates, respectively. Heydari et al. (2018) showed an optimum planning combined with regular repair and maintenance work enables reducing the maintenance budget from 25–73% during the first years. In this study in all climate zones, UPCI values for roads with a low traffic were higher than two other traffic levels. A similar finding was recorded by Girardin et al. (2022). They showed that the narrow and low-traffic roads tended to degrade more rapidly over time. Moreover, Ciobanu et al. (2012) found that the degradation forms of forest roads and their extending on the gravel forest road is affected by traffic volume.

Different climates are resulting in weather events, frequency of peak flows, temperature, and evaporation patterns, precipitation time, duration and form and that these factors will have a significant impact on the road wearing course quality (Dodson 2021). From the analysis of mean data it is observed that important difference exists among climates. Sub-humid climate significantly presented lower UPCI (7.19) compared to the two other climates. This result was in agreement with the findings of Akgul et al. (2017) which indicated that that volumetric degradation on forest road surface is related to meteorological factors especially total rainfall. In humid climates, thunderstorms often cause heavier rain than two other climates and this make sever runoff flow (Fidelus-Orzechowska et al. 2018). In humid climate, changes in precipitation can rapidly alter the moisture content in the road foundations and influence wearing course deterioration. Water will enter the wearing course causing potholing and will cause a rapid loss of surface condition (Shao et al. 2017; Akgul et al. 2017). Chamorro Giné and Tighe (2019) successfully developed a framework for sustainable rural road networks for roads in arid, Mediterranean, and humid climates. Fidelus-Orzechowska et al. (2020) used terrestrial laser scanner to analysis of surface changes on an abandoned forest road. Research has shown that there is a significant relationship between the flow velocity and the magnitude of damage on forest road. Qiao et al. (2020) used life-cycle cost analysis (LCCA) to find economic climate adaptation method and improve International Roughness Index (IRI) of road in Virginia (humid and sub-tropical climates) for period 2020–2039. They reported that road wearing course is affected by climate factors including air temperature, precipitation, wind speed, sunshine percentage, and humidity. Findings of this study lead to a 1–5% reduction in IRI, a 4–14% reduction in rutting, and a 3–53% reduction in cracking.

In Mediterranean climate where high and medium-traffic roads were maintained by high-budget strategy, deterioration time was longer than other maintenance strategies and maintenance number per decade was lower. High-budget maintenance activities include one drainage and culvert improvement per two km, heavy blading with reshaping, forming and compaction, 100 mm layer gravelling and pothole patching (Chamorro Giné and Tighe 2019). In low traffic roads a more effectiveness was observed for low budget maintenance and rehabilitation cycle (3.4 per 10 years) was longer compared to the other strategies. In semi-arid climate where high traffic roads were maintained by low budget strategy, deterioration time was longer than other maintenance strategies and number of maintenance per decade was lower. Low-budget maintenance activities include one drainage and culvert improvement per 6 km, light blading or grading, 30 mm layer gravelling and pothole patching (Chamorro Giné and Tighe 2019). In low and medium traffic roads a more effectiveness was observed for high budget maintenance and rehabilitation cycle was longer compared to the other strategies. In sub-humid climate, where high, medium and low traffic roads were maintained by high-budget strategy, deterioration time was longer than other maintenance strategies and number of maintenance per decade was lower.

In Mediterranean and semi-arid climate zones it was observed that in most cases, CE values of low-budget maintenance strategy were more efficient than other strategies in all traffic levels. The reason for this is that low maintenance funding is more cost-effective than other funding levels in long-term. In sub-humid climate, CE values severely vary depending on the level of traffic. Medium, high and low-budget maintenance strategies were respectively efficient in high, medium and low-traffic roads based on CE values

Conclusions

Totally forest road wearing course must be adapted in response to different climates in order to long term service. This study attempted to indentify suitable maintenance strategy and budget to improve resistance of road surfacing layer against different traffic levels. Forest road wearing course reconstruction projects, especially in areas where pedestrian’s forest machines are done every day, often creates cost, difficulties and limited access to the road users; therefore, it is necessary to plan for the adoption of appropriate practices to minimize the damage of investment in forest roads. In this study, it was concluded that the effects of maintenance budget differ among climates. In a sub-humid climate, high-budget maintenance activities not only performed better over time but was also economically advantageous compared to other budgets, especially in medium-traffic roads. In a semi-arid climate, low-budget maintenance activities are only effective in high-traffic roads, in contrast, medium-budget activities was effective in medium and low-traffic road with low bearing capacity and surfacing quality. Low-budget maintenance activities were cost-effective for the sustainable management of roads in the Mediterranean climate. Overall, it was concluded that monitoring UPCI over time and probability analysis using time series is useful for sustainable and long-term management of forest roads. This research provided new techniques and tools necessary for cost-effective maintenance and sustaining access to forests in three climate zones of Hyrcanian forests. Moreover, Monte Carlo time series is a prospective method in predictions and solving forest road wearing course problems.

Declarations

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Authors' contributions A. Parsakhoo and A. Rezaee performed the analysis and took the lead in writing the manuscript. A. Najafi and J. Mohammadi helped with the interpretation. All authors contributed to the manuscript and read and approved of its final version.

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Data availability Data used and produced in this study may be available on request (Aidinparsakhoo@yahoo.com).

Conflicts of interest The authors declare that they have no conflict of interest.

References

1. Akgul M, Yurtseven H, Akburak S, Demir M, Cigizoglu HK, Ozturk T, Eksi M, Akay· AO (2017) Short term monitoring of forest road pavement degradation using terrestrial laser scanning. Measurement 103: 283-293. https://doi.org/10.1016/j.measurement.2017.02.045
2. Akgul M, Akburak S, Yurtseven H, Akay A, Cigizoglu H, Demir M, Ozturk T, Eksi M (2019) Potential impacts of weather and traffic conditions on road surface performance in terms of forest operations continuity. Appl Ecol Environ Res 17:2533-2550. http://dx.doi.org/10.15666/aeer/1702_25332550
3. Aruga K, Sekiguchi T, Sato T, Shuin Y (2022) Evaluation of forest road damages using return periods caused by heavy rains in Kanuma and Nikko cities of Tochigi Prefecture, Japan. Forestist 72:29-40. http://dx.doi.org/10.5152/forestist.2021.21013
4. Akay AE (2006) Minimizing total costs of forest roads with computer-aided design model. Sadhana 31:621–633. http://dx.doi.org/10.1007/BF02715918
5. Akay AO, Akgul M, Demir M, Acar HH (2020) Analysis of factors associated with the amount of forest road reconstruction activity in Turkey: Autoregressive distributed lag modelling approach. For Ecol Manage 458:117-125. https://doi.org/10.1016/j.foreco.2019.117800
6. Akay AE, Serin H, Sessions J, Bilici E, Pak M (2021) **Evaluating the effects of improving forest road standards on economic value of forest products.** Croatian J For Eng 42:245-258. http://dx.doi.org/10.5552/crojfe.2021.851
7. Bicici S, Zeybek M (2020) An approach for the automated extraction of road surface distress from a UAV-derived point cloud. Automat Cons 122:57-64. http://dx.doi.org/10.1016/j.autcon.2020.103475
8. Chamorro Giné MA, Tighe S (2019) Development and application of a sustainable management system for unpaved rural road networks. J Trans Res Board 12: 1-11. https://doi.org/10.1177/0361198119864908
9. Chamorro Giné MA, Tighe S (2009) Development of a management framework for rural roads in developing countries. J Trans Res Board 2093: 99-107. https://doi.org/10.3141/2093-12

10. Ciobanu V, Alexandru V, Saceanu S (2012) Degradation forms of forest gravel road roadways under heavy vehicles used in timber transport. Agric Food Eng 5:37-45. http://webbut2.unitbv.ro/BU2012/Series%20II/BULETIN%20II%20PDF/Ciobanu_V.pdf
11. Dadrasjavan F, Zarrinpanjeh N, Ameri A (2019) Automatic crack detection of road pavement based on aerial UAV imagery. Civil Eng 146: 1-16. https://doi.org/10.20944/preprints201907.0009.v1
12. Dodson EM (2021) Challenges in forest road maintenance in North America. Croatian J For Eng 42:107-116. https://doi.org/10.5552/crojfe.2021.777
13. Ferenčík M, Kardoš M, Allman M, Slatkovská Z (2019) Detection of forest road damage using mobile laser profilometry. Comput & Elec Agri 166: 48-55. https://doi.org/10.1016/j.compag.2019.105010
14. Fidelus-Orzechowska J, Strzyżowski D, Cebulski J, Wrońska-Wałach D (2020) A quantitative analysis of surface changes on an abandoned forest road in the Lejowa Valley (Tatra Mountains, Poland). Remote Sens 12: 3467-3475. https://doi.org/10.3390/rs12203467
15. Fidelus-Orzechowska J, Strzyżowski D, Żelazny M (2018) The geomorphic activity of forest roads and its dependencies in the Tatra Mountains. Geogr Annal Ser A Phys Geogr 100:59-74. https://doi.org/10.1080/04353676.2017.1376585
16. Fraefel M, Bont L, Fischer Ch (2021) Spatially explicit assessment of forest road suitability for timber extraction and hauling in Switzerland. Euro J For Res 140:1195-1209. https://doi.org/10.1007/s10342-021-01393-w
17. Girardin P, Valeria O, Girard F (2022) Measuring Spatial and Temporal Gravelled Forest Road Degradation in the Boreal Forest. Remote Sens 14:457-465. https://doi.org/10.3390/rs14030457
18. Gotosa J, Nyamadzawo G, Mtetwa T, Kanda A, Dudu VP (2015) Comparative road dust suppression capacity of molasses stillage and water on gravel road in Zimbabwe. Advance Res 3:198-208. https://doi.org/10.9734/AIR/2015/13019
19. Goudarzi R, Najafi A (2018) Multi-criteria decision-making methods in the management of forest road maintenance. J For Wood Product 70: 111-119. https://doi.org/10.22059/JFWP.2018.214809.776
20. Guo X, Hao P (2021) Using a random forest model to predict the location of potential damage on asphalt pavement. *Appl Sci 11*:103-111. https://doi.org/10.3390/app112110396
21. Grajewski SM (2016) Influence of pavement moisture content on the load-bearing capacity of forest road. Infra Ecol Rural Areas 4: 1451-1462. https://doi.org/10.14597/infraeco.2016.4.2.107
22. Hrůza P, Mikita T, Tyagur N, Krejza Z, Cibulka M, Procházková A, Patočka Z (2018) Detecting forest road wearing course damage using different methods of remote sensing. Remote Sens *10*:492-500. https://doi.org/10.3390/rs10040492
23. Heidari MJ, Najafi A, Alavi SJ (2018) Pavement deterioration modeling for forest roads based on logistic regression and artificial neural networks. Croatian J For Eng 39:271-287. http://www.crojfe.com/site/assets/files/4251/heidari.pdf
24. Maeda H, Sekimoto Y, Seto T, Kashiyama T, Omata H (2018) Road damage detection and classification using deep neural networks with smartphone images. Comput Aided Civil Infrastruct Eng 33: 1127-1141. https://doi.org/10.1111/mice.12387
25. Osorio-Lird A, Chamorro A,Videla C, Tighe S, Torres-Machi C (2018) Application of Markov chains and Monte Carlo simulations for developing pavement performance models for urban network management. Struc Infra Eng 14:112-119. https://doi.org/10.1080/15732479.2017.1402064

26. Pazhouhan I, Fathizadeh O, Kamkar Rouhani A, Vahidi J, Najafi A (2020) Time and cost simulation of forest roads construction using Monte Carlo analysis. Ecol Iranian For 8:128-135. http://ifej.sanru.ac.ir/article-1-297-fa.pdf
27. Parsakhoo A, Hosseini SA, Lotfalian M, Mohammadi J, Salarijazi M (2021) Efficiency of different anti-dust agents in reducing dust emission from forest road and deposition on leaf surface. Croatian J For Eng 42:269-282. https://doi.org/10.5552/crojfe.2021.740
28. Qiao Y, Santos J, Stoner AMK, Flinstch G (2020) Climate change impacts on asphalt road pavement construction and maintenance. J Indus Ecol 24:342-355. https://doi.org/10.1111/jiec.12936
29. Ruzgienė B, Aksamitauskas Č, Daugėla I, Prokopimas Š, Puodžiukas V, Rekus D (2015) UAV photogrammetry for road surface modeling. The Baltic J Road Bridge Eng 10:151–158. https://doi.org/10.3846/bjrbe.
30. Saha P, Ksaibati K (2017) Developing an optimization model to manage unpaved roads. J Advanc Trans 2017: 1-11. https://doi.org/10.1155/2017/9474838
31. Setyawan A, Nainggolan J, Budiarto A (2015) Predicting the remaining service life of road using pavement condition index. Procedia Eng 125:417-423. https://doi.org/10.1016/j.proeng.2015.11.108
32. Shao Z, Jenkins G, Oh E (2017) Assessment the impacts of climate change on road infrastructure. Int J Geo 13:120-128. https://doi.org/10.21660/2017.38.72099
33. Tan Y, Li Y (2019) UAV Photogrammetry-based 3D road distress detection. Int J Geo-Infor 8:1-24. https://doi.org/10.3390/ijgi8090409
34. Yurtseven H, Akgul M, Akay AO, Akburak S, Cigizoglu HK, Demir M, Ozturk T, Eksi M (2019) High accuracy monitoring system to estimate forest road surface degradation on horizontal curves. Environ Monit Assess 191:1–17. https://doi.org/10.1007/s10661-018-7155-8
35. Yoshida M, Takahashi H, Sakai H (2016) Analysis of alternative forest road retaining technologies on difficult slopes in Japan. Euro J For Eng 2: 61–66. https://dergipark.org.tr/en/download/article-file/263193

Tables

Table 1
General characteristics of study areas

Study area	Mediterranean zone (Shastkalateh)	Sub-humid zone (Rezaeian)	Semi-Arid zone (Arabdagh)
Coordinate	54°21´26´´ to 54°24´57´´ N 36°43´27´´ to 36°48´06´´ E	55°01´00´´ to 55°06´30´´ N 36°52´30´´ to 36°48´01´´ E	55°37´04´´ to 55°47´07´´ N 37°32´01´´ to 37°36´05´´ E
Forest extent (ha)	1713.3	12465	2240
Elevation range (m)	230–700	790–1270	200–955
Lithology	Lime and sandstone (conglomerate)	Lime - Marl and dolomite lime	Lime – loess deposits
Soil type	Silt clay loam- Silt clay	Silt clay loam- Silt clay	Silt loam- Silt clay loam
Mean annual rainfall (mm)	526	583.1	536.7
Mean annual temperature(°C)	15.4	12.9	16.9
Aridity index	20.71	25.46	19.95
Dominant forest species	*Carpinus betulus L., Parrotia persica C.A.Mey*	*Carpinus betulus L., Tilia Begonifolia*	*Carpinus betulus L., Zelkova carpinifolia*
Road length (km)	30.3	108.8	25
Road density (m ha^{-1})	18.1	8.4	11.1

Table 2
UPCI values for gravel roads in different climates
(Chamorro Giné and Tighe 2019)

Condition	Semi-Arid	Mediterranean	Sub-Humid
Very good	8.2 to 10	8.2 to 10	8.2 to 10
Good	5.2 to 8.1	5.7 to 8.1	7.2 to 8.1
Regular	4.2 to 5.1	4.7 to 5.6	5.2 to 7.1
Poor	2.2 to 4.1	2.7 to 4.6	3.7 to 5.1
Very poor	1 to 2.1	1 to 2.6	1 to 3.6

Table 3
Traffic levels

Traffic volume	Low traffic	Moderate traffic	High traffic
Average Daily Traffic (ADT)	< 10	10–20	> 20

Table 4
Road maintenance strategies in different budget levels

Maintenance strategy	Low budget	Medium budget	High budget
Drainage and culvert improvement	1 per 6 km	1 per 4 km	1 per 2 km
Grading	Light blading or grading	Heavy blading or grading with localized compaction	Heavy blading with reshaping, forming and compaction
Local gravelling, Pothole patching	6m^3 per km	12m^3 per km	18m^3 per km
Gravelling	30 mm layer	60 mm layer	100 mm layer

Table 5 Analysis of variance for the effects of independent variables on UPCI

Source	df	Sum squares	Mean squares	F
Corrected model	26	184.72	7.10	6.10**
Intercept	1	12935.92	12935.92	1.111E4**
Climate	2	38.45	19.22	16.51**
Maintenance strategy	2	63.45	31.73	27.25**
Traffic	2	44.63	22.32	19.17**
Climate× Maintenance strategy	4	5.51	1.38	1.18^{ns}
Climate×Traffic	4	19.37	4.84	4.16*
Maintenance strategy×Traffic	4	1.68	0.42	0.36^{ns}
Climate×Maintenance strategy×Traffic	8	11.08	1.39	1.19^{ns}
Error	189	220.05	1.16	
Total	216	13355.03		
Corrected total	215	404.77		

*, ** significant at probability level of 95 and 99%, respectively; ns: is not significant

Table 6
Time to deterioration and maintenance cycle according to maintenance strategy and traffic

Maintenance Strategy	Mediterranean		Semi-arid		Sub-humid	
	Time to deterioration (month)	Maintenance per 10 years	Time to deterioration (month)	Maintenance per 10 years	Time to deterioration (month)	Maintenance per 10 years
Low B & high T*	14	8.6	36	3.3	10	12
Medium B & high T	15	8.0	32	3.7	14	8.6
High B & high T	16	7.5	28	4.3	20	6.0
Low B & medium T	27	4.4	18	6.7	19	6.3
Medium B & medium T	33	3.6	46	2.6	19	6.3
High B & medium T	35	3.4	49	2.4	43	2.8
Low B & low T	35	3.4	19	6.3	18	6.7
Medium B & low T	32	3.7	52	2.3	23	5.2
High B & low T	28	4.3	54	2.2	24	5.0
*B: Budget; T: Traffic						

Table 7
Cost-effectiveness analysis of maintenance strategies in different traffic levels

Maintenance Strategy	Mediterranean			Semi-arid			Sub-humid		
	E	UE	CE	E	UE	CE	E	UE	CE
Low B & high T*	81.2	38.2	1.35	210.5	50.2	3.51	23.3	27.9	0.39
Medium B & high T	70.2	45.9	0.68	214.3	52.3	2.09	71.2	62.1	0.69
High B & high T	147.9	53.6	0.95	240.1	62.6	1.55	84.6	52.5	0.54
Low B & medium T	95.5	44.5	1.59	69.9	52.8	1.16	28.0	47.5	0.47
Medium B & medium T	104.7	49.8	1.02	176.6	55.7	1.72	42.9	53.8	0.42
High B & medium T	77.4	54.3	0.50	202.8	61.0	1.31	125.5	62.4	0.81
Low B & low T	27.7	44.6	0.46	29.3	55.3	0.49	15.1	51.7	0.25
Medium B & low T	30.1	49.8	0.29	71.4	56.3	0.70	18.9	57.1	0.18
High B & low T	26.3	54.3	0.17	74.7	59.7	0.48	23.8	60.3	0.15

*B: Budget, T: Traffic, E: Effectiveness, UE: Unit Effectiveness, CE: Cost Effectivenes

Figures

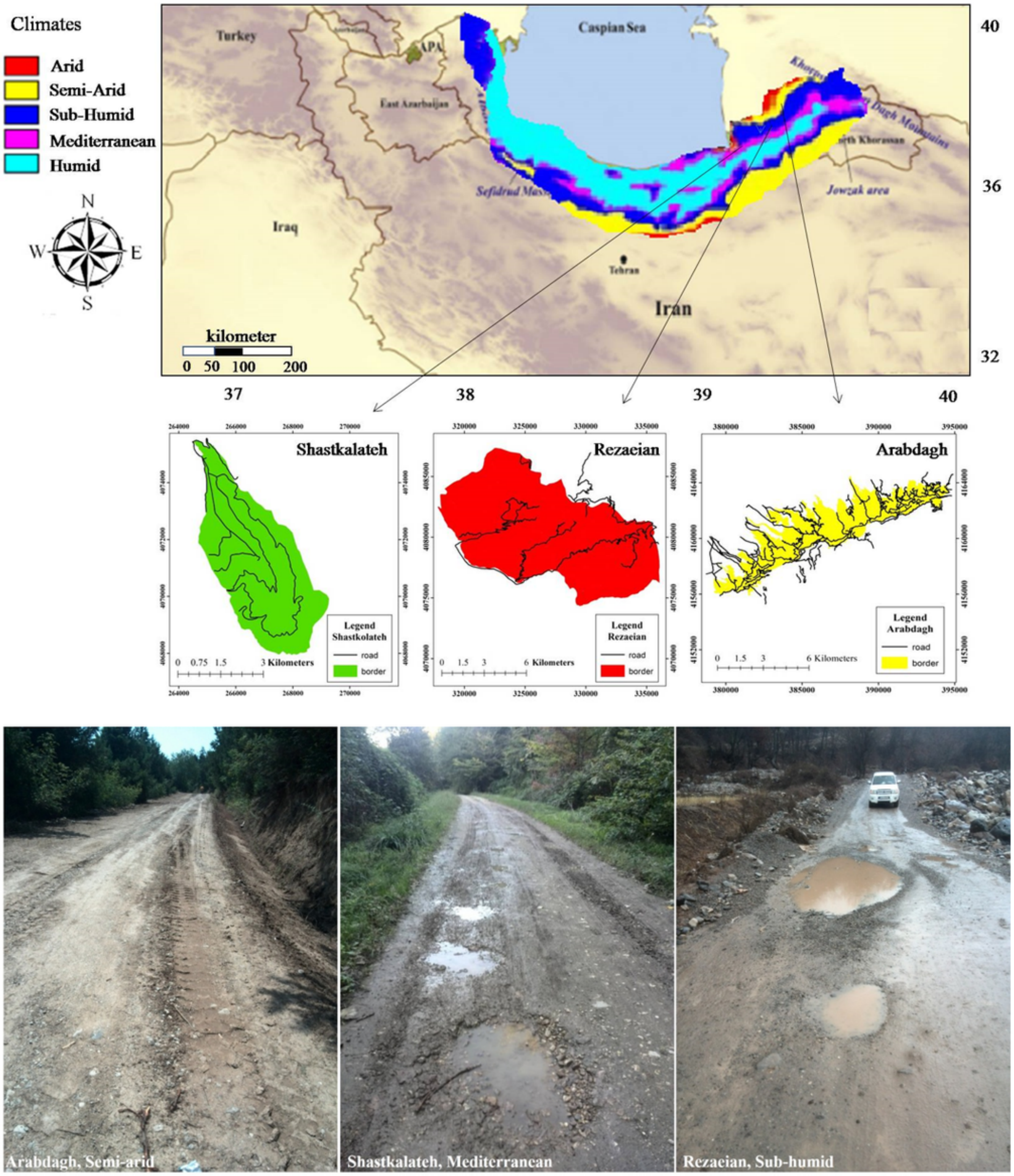

Figure 1

The position of the study areas according to the classification of Hyrcanian forest climate using de Martonne aridity index

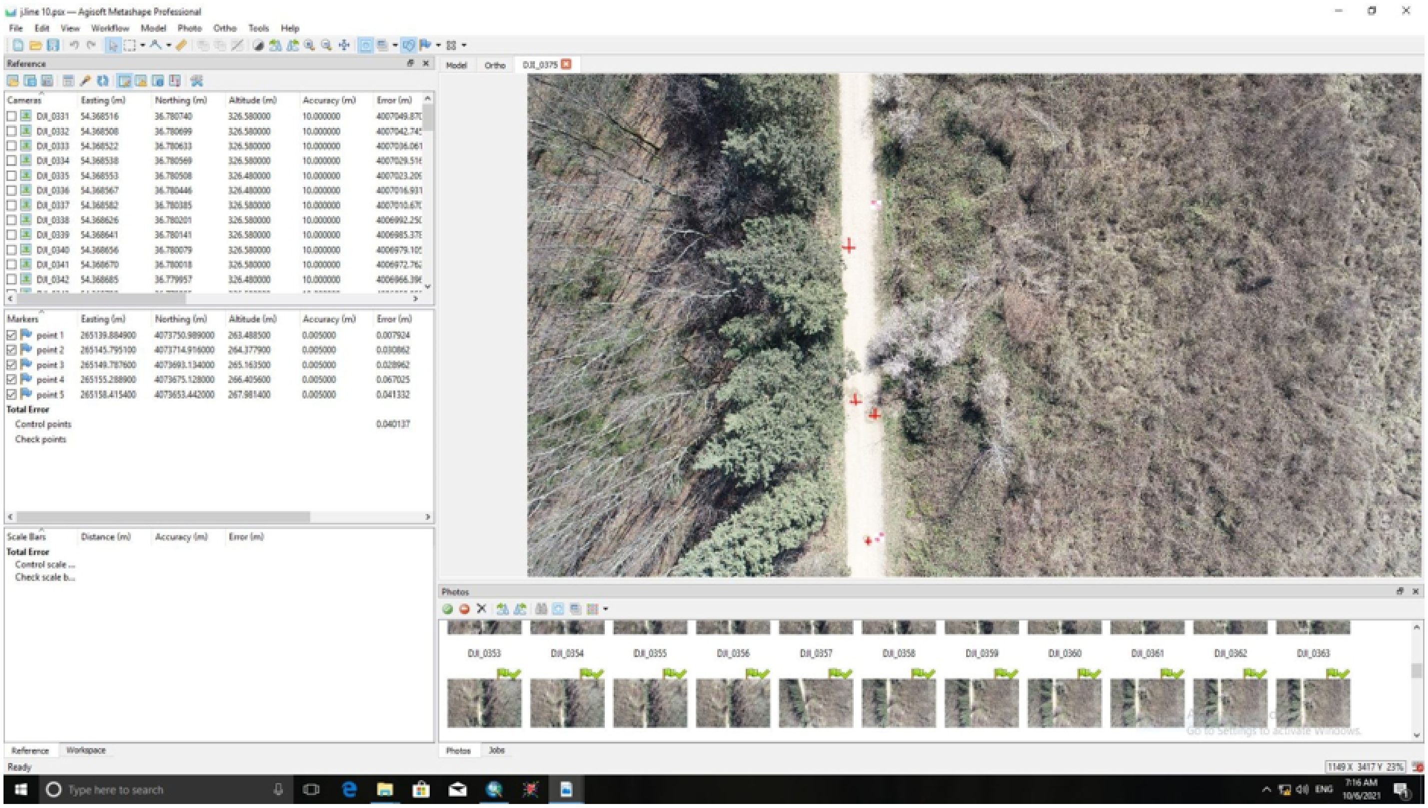

Figure 2

UAV image of road surface and *Agisoft* processing.

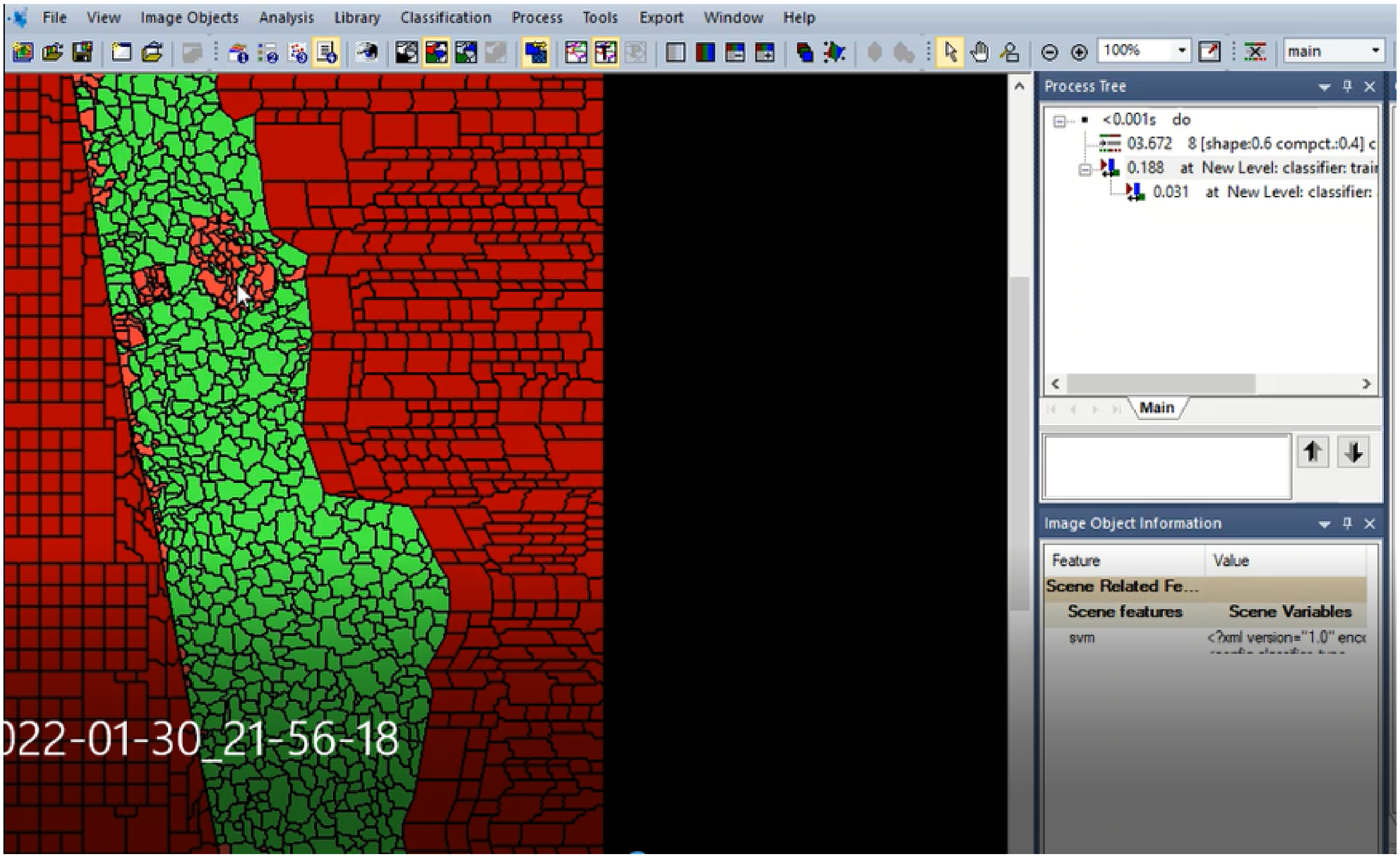

Figure 3

Auto classification and detection of wearing course damage in SVM.

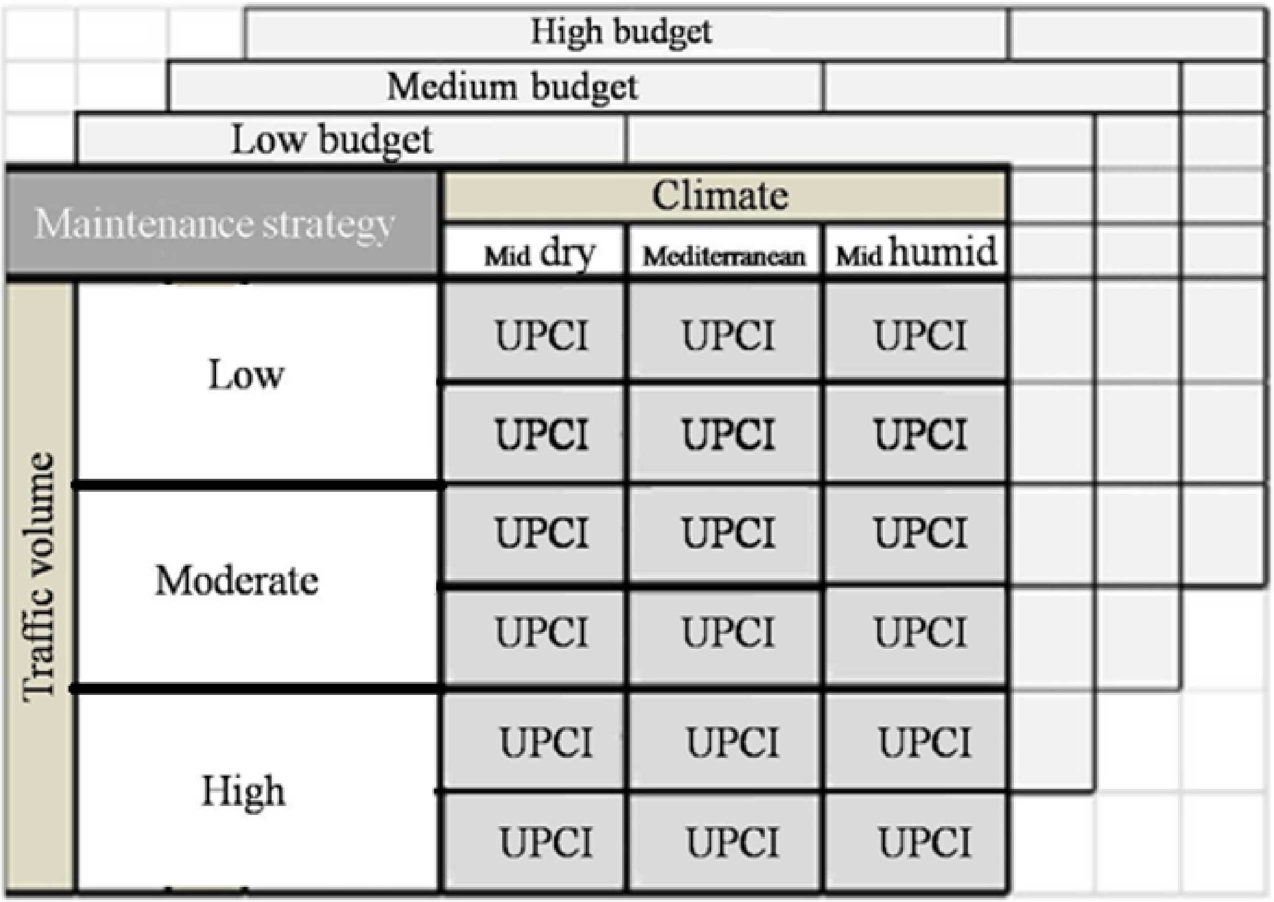

Figure 4

Factorials to assess the effect of traffic, budget and climate on UPCI.

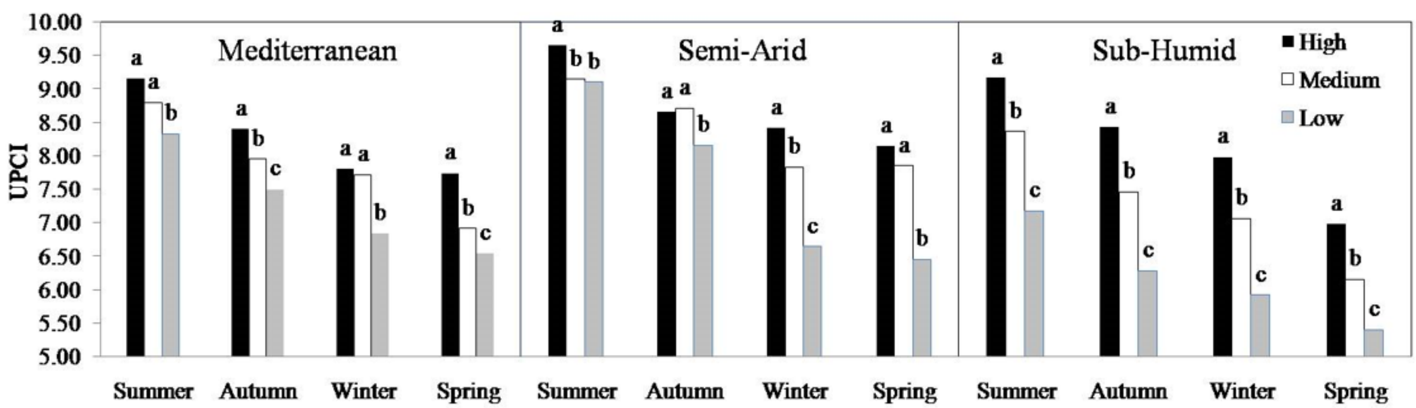

Figure 5

Comparisons of UPCI among different mainenance budget levels in Mediterranean, semi-arid and sub-humid climates (different letters shows significant differences at probability level of 5%).

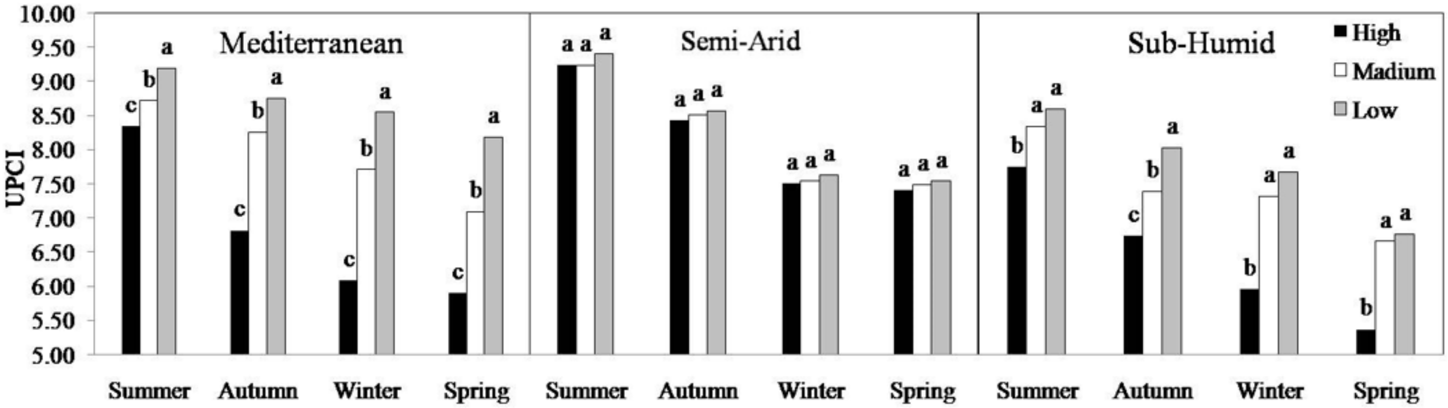

Figure 6

Comparisons of UPCI among different traffic levels in Mediterranean, semi-arid and sub-humid climates (different letters shows significant differences at probability level of 5%).

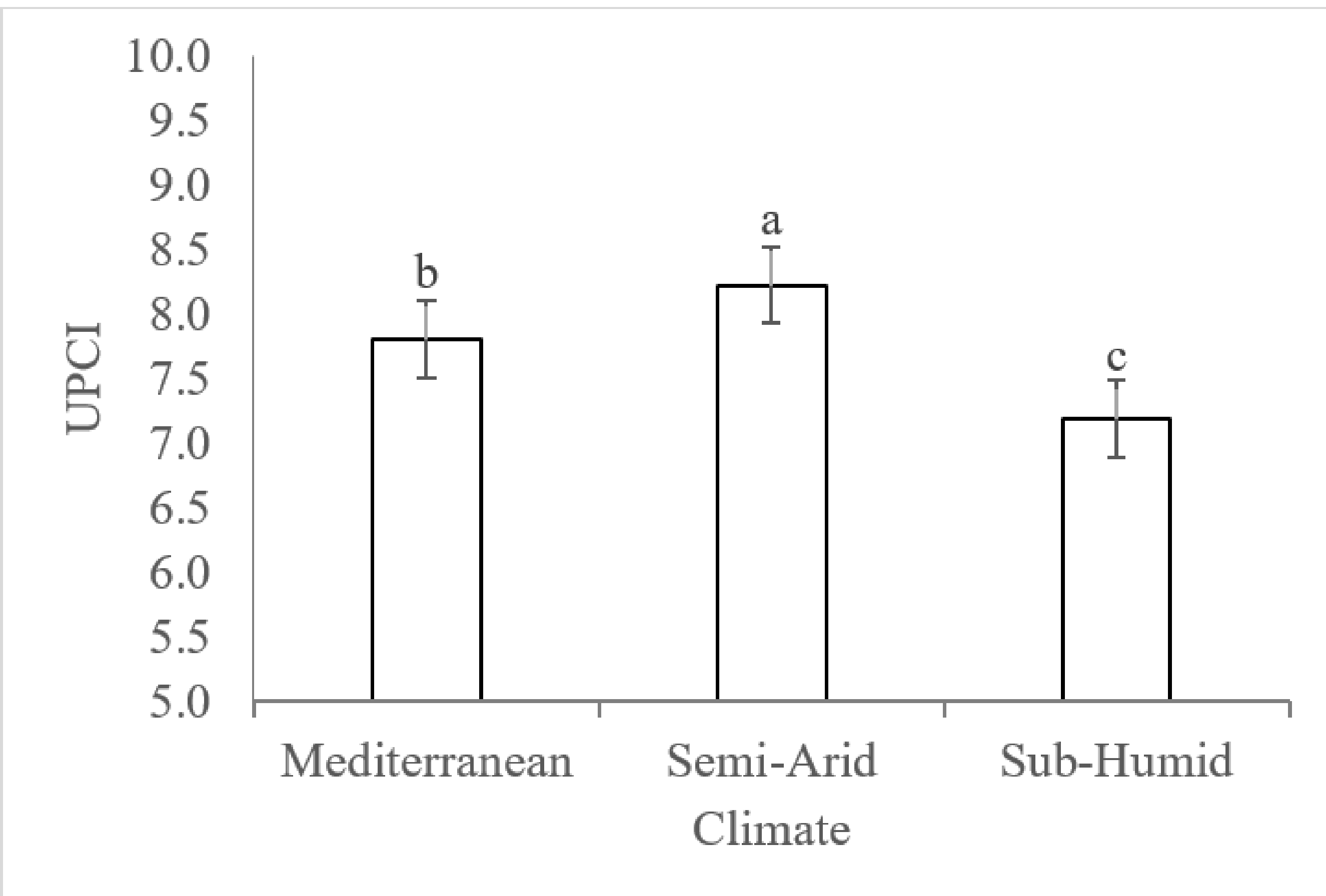

Figure 7

Comparisons of UPCI among different climates (different letters shows significant differences at probability level of 5%).

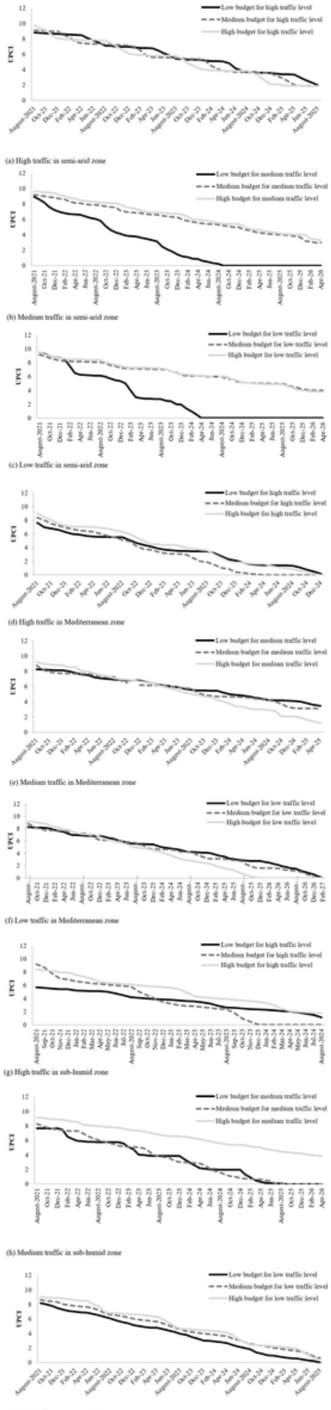

Figure 8

UPCI performance curves over time for roads with different maintenance strategy and traffic levels in semi-arid, Mediterranean and sub-humid climates