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Complex Optimization of Heavy Duty Asphalt Pavement Types in DURABROADS Project

L. Gáspár a*, D. Castro-Fresno b, D. Jato-Espino b, I. Indacochea-Vega b, I. Paeglite c, P. Pascual-Muñoz b, V. Haritonovs c, R. Casado Barrasa d, Z. Bencze a, J. Diez e

aKTI Non-Profit Ltd, 3-5 Thán Károly Str., Budapest, 1158, Hungary
bGITECO Research Group, Universidad de Cantabria, Santander, 39005, Spain
cInzenierbuve SIA, Azenes Iela 20, Riga, 1048, Latvia
dACCIONA Infraestructuras S.A., Avenida de Europa 18, Alcobendas, 28108, Spain
eEuropean Union Road Federation, Place Stéphanie 6/B, Brussels, 1050, Belgium

Abstract

DURABROADS, an EU FP7 financed project launched in 2013, and led by the University of Cantabria (Spain) aims at providing a sustainable growth through the development of innovative, cost-effective and more durable pavements. The new generation of pavement is based on innovative eco-friendly nanotechnology-enhanced asphalts as well on the optimization of procedures to build and rehabilitate durable, safer and greener road infrastructure more adapted to climate change and freight corridor traffic loads. One of the objectives of this project is to identify and evaluate the existing constraints concerning currently used road materials of heavily trafficked roads (TEN-T routes) to withstand current road challenges. Due to different traffic and climate features, four European regions (Northern, Central, Western and Southern Europe) were differentiated. The climate change elements critical to various road types were identified, reviewing the pavement deterioration forms they accelerate. The traffic loads on freight corridors were evaluated considering their accelerated pavement deterioration forms. The synergistic effect of extreme climatic and mechanical loads to pavement surface was scrutinised. A comprehensive quantification methodology for extreme traffic and climatic load combinations was suggested including technical (functional), economic, environmental and social-human aspects with appropriate weighing. Then the European region-specific “optimal” asphalt wearing course types and road rehabilitation techniques for TEN-T routes were identified. The region-specific material and procedure optimization utilizes – in addition to the processing of a comprehensive literature survey – the answers coming from 81 experts of 52 European countries.

* Corresponding author: László Gáspár Tel.: +36-30-9401-288; fax: +36-1-2047-980.
E-mail address: gaspar@kti.hu

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institutions to targeted questionnaire. These data were used to develop a decision support model based on AHP and TOPSIS models to facilitate the selection of asphalt pavement types. The results suggested Stone Mastic Asphalt (SMA) as the most suitable alternative in different climate change scenarios evaluated by a sensitivity analysis.

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Keywords: Asphalt pavements; heavy duty asphalt pavements; lifetime engineering; pavement type optimization

1. Background

DURABROADS, an EU FP7 financed project launched in 2013, and led by University of Cantabria (Spain) aims at providing a sustainable growth through the development of innovative, cost-effective and more durable pavements. The new generation of pavement is based on innovative eco-friendly nanotechnology-enhanced asphalts as well as on the optimization of procedures to build and rehabilitate durable, safer and greener road infrastructure more adapted to climate change and freight corridor traffic loads.

2. Synergistic climatic and mechanical loads on European road network

One of the objectives of DURABROADS project is to identify and to evaluate the existing constraints concerning current road materials and construction, maintenance and rehabilitation procedures and techniques to withstand current road challenges (climate change impacts and the high vehicle load of freight corridors) in order to provide to highway managers with more affordable, safer and environment-friendly practices for road asset management purposes. The results of research projects completed all around Europe (such as BEXPRAC) and in other countries as the US were considered as references.

In order to accomplish the planned optimisation, as a first step the medium and long-term, harmful – technical, economic, environmental and social – effects of ever increasing traffic and environmental loads on European highways, primarily the most heavily trafficked TEN-T Routes were identified. The synergetic effect of simultaneous extreme vehicle and climatic loads were concentrated on. The holistic approach applied, based on the principles of lifetime engineering [Sarja, 2010; Gáspár, 2012], covers a much wider spectrum of parameters than the traditional one does. The different performance requirements of the modular elements in a structure with different loads and life expectancies were distinguished. The changing of their load and resistance (reaction) during the whole life time are to be forecasted in order to predict the time of failure. The possible end of the life strategies (e.g. recycling or reuse) will be also taken into consideration in the establishment of optimization criteria.

First, the possible list of pavement structural types was identified to be considered on most heavily trafficked European routes, and the ones, which are in line with the main project ambitions, were selected. Due to their different climatic and traffic features, four European regions (Northern, Western, Southern and Central Europe) were identified for separate analysis. Then the climate change elements critical to various road types were identified reviewing the pavement deterioration forms they accelerate making distinction between the four regions mentioned before. Next, the traffic loads on European highway freight corridors are evaluated.

A European survey was performed to select the typical flexible, semi-rigid (and eventually rigid) pavement structure variants for high heavy road traffic in order to consider them in the investigation. Main emphasis was given to wearing (surface) course types but lower pavement structural layers and sub-grade types were also considered. A questionnaire survey was initiated in order to collect information about the main traffic and technological features of the highly trafficked TEN-T Roads of many European countries. Up to 17 countries (BE, HR, CZ, EE, FR, DE, HU, IT, LT, LV, NO, PT, SK, SI, ES, RS, UK) responded to the questionnaire mentioned – in addition to asphalt pavement types – also rigid (cement concrete) pavement as a widely used pavement type of heavily trafficked roads (TEN-T Trans-European Transport Network Routes) in their countries. However, in
accordance with the agreed ambitions of DURABROADS project, just the flexible and semi-rigid pavement structures with some type of asphalt surfacing above hydraulically bound layers were further considered.

The climate and the extremely high heavy traffic sizes in various European countries are basically different. The regions on Table 1 were selected for the analysis.

### Table 1. Regions selected according their climate and traffic level.

<table>
<thead>
<tr>
<th>Region</th>
<th>Climate</th>
<th>Traffic Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern Europe</td>
<td>Cold</td>
<td>Medium</td>
</tr>
<tr>
<td>Western Europe</td>
<td>Humid</td>
<td>High</td>
</tr>
<tr>
<td>Southern Europe</td>
<td>Hot</td>
<td>Medium</td>
</tr>
<tr>
<td>Central Europe</td>
<td>Continental</td>
<td>Low</td>
</tr>
</tbody>
</table>

The typical wearing course types for flexible pavement structures are also different in the above European regions:

- Northern Europe: asphalt concrete (AC) – stone mastic asphalt (SMA).
- Western Europe: asphalt concrete – stone mastic asphalt – porous asphalt (PA) – hot rolled asphalt (HRA).
- Central Europe: asphalt concrete – stone mastic asphalt.

### 3. Competing asphalt pavement and road rehabilitation types

The specifications in the relevant European Standard [EN 13108, 2008] and the results from a European-wide survey specifically prepared by DURABROADS partners on the selection of typical asphalt wearing courses in various European regions were utilized in choosing the following five alternatives for the analysis:

- Asphalt concrete (AC)
- Very thin asphalt concrete (BBTM)
- Hot rolled asphalt (HRA)
- Porous asphalt (PA)
- Stone mastic asphalt (SMA).

Pavement designers strive for the durable structural resistance of road pavement structures to the synergistic effect of traffic and environmental loads. Besides, the wearing course surface of a road should provide high level safety, comfort and be cost-effective to every highway user. Its main surface characteristics are as follows:

- Skid resistance influencing traffic safety, tyre wear and fuel consumption.
- Transverse and longitudinal evenness affecting users’ comfort.
- Noise inside and outside road vehicles.
- Light reflection on pavement surface influencing the safety of night and wet pavement driving.
- Surface drainage for decreasing the risk of hydroplaning (aquaplaning), water splash or spray.

These aspects are the needs, and all of them are (should be) covered in detail and carefully for the asphalt mix design. During the life time of a road section, due to traffic and climatic loads, the initially usually excellent, structural and surface characteristics of road pavement structures gradually worsen, and later one of them (the so-called critical condition parameter) reaches the intervention limit (below which the further operation of the road without pavement rehabilitation cannot be taken as economic for the highway operator and/or safe for the road users). The main ambition of the pavement structural design is to postpone the time of pavement failure mentioned before, attaining the longest possible pavement life cycle.
It should be taken into account that the typical pavement deterioration forms and the critical failure types are different in the European regions mentioned above. This fact will be considered in the planned investigation within the topic. As it is well known, the asphalt pavements have two typical deterioration processes because of repeated traffic and environmental loads:

- Disintegration (scaling, ravelling, cracking, potholing, etc.).
- Deformation (longitudinal and transversal deformation, rutting etc.).

The critical (characteristic) failure types in the regions of our Continent are also different as a function of their climates and extreme traffic levels:

- Northern Europe: disintegration.
- Western Europe: disintegration.
- Southern Europe: deformation.
- Central Europe: disintegration and deformation.

Selection of disintegration as critical pavement failure type in various European regions can be explained by their very cold and/or rainy winters causing potholing, cracking type asphalt deterioration, especially on the pavements of highly trafficked routes. At the same time, extremely hot summer periods in Southern and Central European countries are (or can be) the reason of early pavement deformation in the form of ruts and/or longitudinal waves. Of course, it does not mean that – in some cases – the other failure type not mentioned above cannot become critical in a specific region, e.g. due to poor pavement mixture design resulting in inappropriate warm performance of asphalt mixture.

The maintenance-rehabilitation procedures themselves are less region-specific than the ones for pavement structural layers are. However, the performance of the repaired layer basically depends on the synergistic effect of traffic and climatic loads in the specific region. That is why it is suggested to perform the comparison separately in the four European regions mentioned above using everywhere the same, following maintenance-rehabilitation techniques for asphalt pavements: cold milling, sprayed surface dressing, (mixed) surface dressing or microsurfacing, resurfacing using grave emulsion, resurfacing using cold asphalt mix, resurfacing using warm asphalt mix, resurfacing using hot asphalt mix, asphalt overlaying without recycling, cement concrete overlaying without recycling, cold-in-place cold recycling, hot-in-place cold recycling, cold-in-plant cold recycling and hot-in-plant cold recycling.

Any patching or crack filling (sealing) techniques, as “routine” maintenance methods are excluded from the planned comparison of road-related maintenance-rehabilitation procedures since they are able to improve the pavement surface condition just locally unlike the other methods listed before that are used on the whole surface.

4. Optimization of heavy duty asphalt pavement types

4.1. Methodology

A multi-criteria decision-making methodology was proposed that can be outlined as an algorithm having the following five main steps:

- Definition of the decision making problem (decision making tree and set of alternatives)
- Processing of the questionnaire answers (preparation, release and analysis of the answers)
- Weighting of criteria (pairwise comparison and aggregation)
- Assessment of alternatives (literature review, characterization and ranking)
- Sensitivity analysis (weighting of criteria)

In order to select the wearing courses meeting the principles of sustainability, the candidate variants were assessed according to the concept of lifetime engineering. The integrated lifetime engineering methodology concerns the development and the use of technical performance parameters to guarantee that the structures meet all
the requirements coming from human conditions, economy, cultural, social and ecological considerations throughout their whole life cycle [Sarja, 2003]. Life cycle expenses are calculated into present value or annual costs by discounting manufacture, construction, maintenance, repair, rehabilitation, reuse, recycling, disposal etc. expenses [Sarja, 2010]. The considerations mentioned are usually at least partly conflicting aspects. Although lifetime engineering was originally developed for buildings and bridges [Landolfo et al., 2011], its basic principles can be readily utilized also for roads [Gáspár, 2008; Gáspár, 2012]. A holistic approach based on a multi-criteria decision-making theory was chosen to properly analyse the wearing course variants. The same kind of methodology was used for the analysis and prioritization of various pavement maintenance and rehabilitation variants.

The economic requirement of lifetime engineering was characterized through the whole life costs of the candidate wearing courses. Therefore, in addition to the initial investment costs, other cost types of each alternative during their lifetimes (like maintenance, operation, rehabilitation costs) were also taken into account. The average European cost levels were considered.

At the same time, the construction, maintenance and rehabilitation of highway pavements entail various environmental impacts. In this case, they were summarized in the consideration of life long consumption of non-renewable resources and greenhouse gas – mainly carbon dioxide – emissions.

As the third important aspect of the complex lifetime engineering type analysis of candidate wearing courses, the social aspects were characterized by comfort (mostly driving quality) and safety (pavement surface-vehicle wheel interaction).

For the fourth technical aspect, key indicators for the mechanical behaviour (deformation and disintegration) of a wearing course were considered that exist in methodologies for new and reconstructed pavements [COST, 2008]. The four requirements mentioned above were grouped into several criteria and indicators that can be considered as a hierarchical tree-shaped structure (Table 2).

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Criteria</th>
<th>Indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economy</td>
<td>Cost</td>
<td>LCCA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Initial investment</td>
</tr>
<tr>
<td>Environment</td>
<td>Resource efficiency</td>
<td>Aggregates usage</td>
</tr>
<tr>
<td></td>
<td>Consumptions</td>
<td>Bitumen usage</td>
</tr>
<tr>
<td></td>
<td>Emissions</td>
<td>Energy consumption</td>
</tr>
<tr>
<td>Society</td>
<td>Comfort</td>
<td>Ride quality</td>
</tr>
<tr>
<td></td>
<td>Safety</td>
<td>Noise</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Skid resistance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aquaplaning</td>
</tr>
<tr>
<td>Technique</td>
<td>Mechanical Resistance</td>
<td>Disintegration resistance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Deformation resistance</td>
</tr>
</tbody>
</table>

Different approaches were considered for rating the alternatives with respect to each criteria:

- Profound revision of technical literature including research papers, congress proceedings, information released on the topic by road platforms and professionals, etc.
- Opinion on experts collected through specifically designed questionnaires.
- An environmental assessment/life cycle assessment of all the alternatives carried out by the authors.
- A life cycle cost assessment also considering all the alternatives carried out by the authors.
4.2. Processing of questionnaires

The opinions of a road management expert panel needed for the planned pavement type optimization were gathered by asking them to fill in two types of specially designed questionnaires (weighting of criteria and assessment of alternatives). The experts had only to answer to questions on the relative weights of the criteria investigated and the assessment of wearing course or rehabilitation method alternatives. They had to choose from among the following scales when weighting the criteria: Absolutely less important, Much less important, Less important, Slightly less important, Equally important, Slightly more important, More important, Much more important and Absolutely more important. The scales applied for alternative assessment were as follows: Extremely poor, Very poor, Poor, Medium poor, Fair, Medium good, Good, Very good and Extremely good.

The questionnaires mentioned on the weights of criteria and the rating of alternatives were filled in by the DURABROADS partners, as well as by private and public sector experts with extensive knowledge in the field concerned. A total of 81 highly recognized worldwide experts from 52 institutions filled the questionnaires in. However, after discarding for further analyses those questionnaires sent back without being completely filled, 74 of them finally provided valid judgments for weighting the criteria and 25 for assessing the alternatives.

4.3. Weighting of criteria and ranking of alternatives

The relative weights of questionnaire replies were determined using the importance of the elements listed in point 4.2. The pairwise comparisons provided by the experts were related to the preference scale of the Analytic Hierarchy Process (AHP), created by Saaty (1980). To quantify the pairwise comparisons required for that purpose, Saaty (1980) proposed a scale as represented in Table 3.

<table>
<thead>
<tr>
<th>Linguistic term (comparison of j₁ and j₂)</th>
<th>Numerical value j₁ with respect to j₂</th>
<th>Numerical value j₁ with respect to j₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equally important</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Slightly more important</td>
<td>3</td>
<td>1/3</td>
</tr>
<tr>
<td>More important</td>
<td>5</td>
<td>1/5</td>
</tr>
<tr>
<td>Much more important</td>
<td>7</td>
<td>1/7</td>
</tr>
<tr>
<td>Absolutely more important</td>
<td>9</td>
<td>1/9</td>
</tr>
</tbody>
</table>

As for the ranking of alternatives, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [Hwang and Yoon, 1981] has been used based on the rating of alternatives and the weighting criteria previously evaluated.

The TOPSIS method is structured as follows:
- Definition of the decision-making matrix
- Normalization of the decision-making matrix
- Construction of the normalized weighted decision-making matrix
- Determination of the positive ideal solution and negative ideal solution
- Calculation of the distance of each alternative from A⁺ and A⁻
- Calculation of the relative closeness from each alternative to the ideal solution.

4.4. Sensitivity analysis

A sensitivity analysis was carried out to evaluate the effect of potential climate change scenarios in the final ranking resulted from the multi-criteria decision methodology. Thus, the most likely climate change projections in the European regions were identified, and their potential impact on the criteria weighting were hypothesized in the
short and long-term scenarios. Besides, another scenario was added to reflect the lower durability of asphalt pavements in Northern European countries [OECD, 2005]. In this sense, the lower durability of the asphalt materials in the Northern Countries will impact on the life cycle and life cycle cost analysis of the alternatives and on the importance of the technical criteria against other criteria.

Regarding climate change effects, the global increase of the annual temperatures, solar radiation and consecutive hot days are expected to increase rutting and aging problems in the asphalt mixture in Southern and Central European countries. On the other hand, the increase of raining events will reduce road safety in Western and Northern European countries. Other side effects such as the increase of thawing periods in Central and Northern countries were also considered. Finally, long-term scenarios will include the increase concern of society regarding climate change and therefore the growing importance of environmental criteria against economic criteria.

4.5. Results and discussion

According to the analysis and optimization of candidate asphalt wearing courses, the technical (functional) performance highlighted as the preponderant requirement. This is clearly in agreement with the fact that an adequate mechanical behaviour would have very likely good economic and social performances, too. Following, the environmental criteria are considered of primary importance among stakeholders probably due to the global increasing awareness and emphasis on ecological dangers. Likewise, user safety is the most relevant social factor and its weight slightly overtakes the economic criteria.

Regarding the final ranking of alternatives, the multi-criteria decision methodology presents the SMA mixes as the best wearing course option followed by HRA, BBTM, AC and finally PA. The final results of the methodology will depend on the expected durability of each type of asphalt mixture since this will affect the life cycle and life cycle cost assessment. Although in this case study average data from literature have been used, in a real project, specific case-to-case data should be used in order to reduce uncertainty of the results (according to the literature, PA mixes presents an average service life from 4 to 14 depending on the source consulted).

The effect of potential climate change in the selection of alternatives is noticeable, although SMA maintains its first position as the most suitable mixture. According to the results, in the long-term, the use of thin layers will increase in importance due to its lower resource consumption and therefore its lower CO₂ emissions. Besides, in those scenarios with increasing rain events, safety might become an even more relevant issue, making PA mixes a better alternative for the user.

5. Concluding remarks

DURABROADS project aims at providing a sustainable growth through the development of innovative, cost-effective and more durable pavements. One of its objectives is to identify and to evaluate the existing constraints concerning current road materials and rehabilitation procedures to withstand current road challenges (climate change impacts and the high vehicle load of freight corridors) in order to provide to highway managers with more affordable, safer and environment-friendly practices for road asset management purposes. As a part of the project activities, European asphalt wearing courses and road rehabilitation techniques used on heavily trafficked pavements were ranked using comprehensive questionnaire survey.

The high number of European-wide questionnaire replies were analysed by a new decision support model based on the combination of the AHP and TOPSIS methods. The results obtained show the usefulness of the model and the clairvoyance that provides decision-makers to select the most suitable wearing course according to sustainable development criteria based on the use of the principles of lifetime engineering. Even though properly managing roads can have great positive impacts on economy, environment and society, there are few methodologies intended to assist this kind of selection processes, highlighting also the importance and interest of the multi-criteria decision making methodology that had been tailor-made for the present analysis. It should be also noticed that the structuring of this decision-making problem into a hierarchical tree allows obtaining partial conclusions about the performance of the alternatives with respect to a certain aspect or factors influencing them.
Acknowledgement

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