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# Cost-Effective Strategies for Regional Road Network Management: The Role of Reclaimed Asphalt Pavement Materials and Urban Factors

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ABSTRACT

**Purpose**: Our article addresses road-cost management at the regional level—an area less studied than local roads or highways. The study aims to identify critical, long-term urban factors that lead to higher regional road-management costs and to propose a financially sustainable strategy for road-network reconstruction using various reclaimed asphalt pavement (RAP) materials.

**Methodology**: Using stepwise and enter regression analyses with data on road quality and maintenance costs in Czechia, the study considers factors such as elevation, slope, and changes in population and population density.

**Findings:** The results highlight that slope and road class—both of which are linked to the disconnectedness of the road network—increase road-maintenance costs. Thus, network renewals implemented in compact sets of roads can significantly reduce costs. By contrast, population and population density have only a minimal impact on long-term costs.

**Practical Implications**: We define scenarios to reduce costs through RAP materials and determine potential savings, using regional roads in Czechia as an example. The scenarios indicate potential savings of nearly €27 million per region when RAP is employed. In practice, using RAP materials can enable infrastructure managers to renew more than one-third of roads each year compared with conventional mixes, or to increase the frequency of restoring lower-quality road sections from every three years to every 2.25 years.

**Value**: The article offers new insights into the factors that determine regional road-level costs. It demonstrates that using RAP materials in regional road management can positively affect the frequency of road revitalisation.

*Keywords: road management, regional roads, RAP, critical cost factors, modernisation, planning, transportation*

## Stroškovno učinkovite strategije za upravljanje regionalne cestne mreže: vloga materialov iz recikliranega asfalta in urbanih dejavnikov

POVZETEK

**Namen:** Prispevek obravnava upravljanje stroškov cest na regionalni ravni. Gre za področje, ki je v primerjavi z lokalnimi cestami in avtocestami precej manj raziskano. Cilj študije je opredeliti ključne dolgoročne urbane dejavnike, ki vodijo k višjim stroškom upravljanja regionalnih cest, ter predlagati finančno vzdržno strategijo obnove cestnega omrežja z uporabo različnih materialov iz recikliranega asfalta (RAP).

**Metodologija:** Na podlagi postopnih in standardnih regresijskih analiz ter podatkov o kakovosti cest in stroških vzdrževanja na Češkem študija upošteva dejavnike, kot so nadmorska višina, naklon ter spremembe števila prebivalcev in gostote poselitve.

**Ugotovitve:** Rezultati poudarjajo, da sta naklon in cestni razred – oba pa sta povezana z razdrobljenostjo cestnega omrežja – ključna vzroka za višje stroške vzdrževanja. Obnove, izvedene na kompaktnih sklopih cest, lahko zato stroške občutno znižajo. Nasprotno pa število prebivalcev in gostota poselitve le minimalno vplivata na dolgoročne stroške.

**Praktična uporabnost:** Na primeru regionalnih cest na Češkem smo oblikovali scenarije za znižanje stroškov z uporabo materialov RAP in določili možne prihranke. Scenariji kažejo, da lahko uporaba RAP prinese skoraj 27 milijonov evrov prihrankov na regijo. V praksi to omogoča upravljavcem infrastrukture, da letno obnovijo več kot tretjino cest v primerjavi s klasičnimi zmesmi ali pa pogostost obnove nižjekakovostnih odsekov povečajo z enkrat na tri leta na enkrat na 2,25 leta.

**Dodana vrednost:** Članek prinaša nova spoznanja o dejavnikih, ki določajo stroške na ravni regionalnih cest, ter dokazuje, da uporaba materialov RAP v regionalnem cestnem gospodarjenju pozitivno vpliva na pogostost revitalizacije cest.

*Ključne besede:* *upravljanje cest, regionalne ceste, RAP, ključni stroškovni dejavniki, modernizacija, načrtovanje, promet*

*JEL: H54, R4, R53*

## 1 Introduction

Investment in transport infrastructure has an essential role in public spending. It has been the subject of many economic and technical studies but has also attracted attention from several humanities disciplines. Transport infrastructure is often considered a prerequisite for a particular economic development potential. Thus, transport infrastructure has quite an irreplaceable place corresponding with the increasingly intensive shift to just-in-time planning systems. Abeysekara et al. (2021) show that road infrastructure accounts for 31% of capital expenditures globally but also acknowledged a significant gap between the demand for large-scale transport infrastructure and investments in such infrastructure.

Many studies focus on material structure and construction of road pavements, discussing the usage of reclaimed asphalt pavement material (RAP) and identifying potential cost savings. Celauro et al. (2017) show that the use of sustainable construction techniques (RAP and lime stabilisation of clayey soils) can lead to the reduction of total cost and thus allow the allocating of more significant financial resources to perform an “ideal” road maintenance plan on the example of local roads. Other studies aim to identify critical factors in road management. The maintenance costs of roads vary with the type of surface, age, and traffic (Nicholls et al., 2016). Haraldsson (2007) found that costs for all operation and maintenance measures increase with traffic intensity. Furthermore, traffic overload is discussed, showing trucks are expected to pay for most of the cost because heavy vehicles are responsible for most road deterioration (Henning et al., 2014). This is confirmed by Pais et al. (2013), who identified that overloaded vehicles could increase pavement costs by more than 100% compared to the cost of identical vehicles with legal loads. Extensive literature discusses road maintenance under specific weather conditions regarding seasonal changes, especially in winter (Ye et al., 2009) or climate change with increasing temperature extremes (Mallick et al., 2014). Moreover, the core of current studies usually lies on local roads (Nassiri et al., 2015) and highways (Cechet, 2005). Even urban factors determining long-term conditions such as population, population density or elevation and slope (mentioned only in particular conditions – see Stückelberger et al., 2006) are rarely discussed in the literature.

The emphasis on mid-level regional road management regarding long-term cost determinants is much less discussed in the literature, and it is scarce to find studies that can bridge the technical, urban and economic focus. The essential goal of our article is to identify critical urban long-term factors leading to higher costs in regional road management and to contribute to defining the financially sustainable strategy for reconstruction and modernisation of the regional road network by comparing scenarios that use or do not use RAP. In the following part of the paper, we first identify the current research knowledge. Second, we describe the data and methods. Third, we will explain Czechia's regional road network, potential technological change, and financial framework. Then, we define the model on road cost urban factors and determine scenarios for future road cost management. Finally, we discuss our results and come to conclusions.

As one of the key problems related to planning infrastructure projects, Chang (2002) identified cost increases and related delays in project schedules. Project average cost overrun is a commonly discussed problem. For example, cost overruns have been identified in the Netherlands (Cantarelli et al., 2012a; Cantarelli et al., 2012b), where the overrun was 18.6% for road infrastructure. Flyvbjerg et al. (2003) reached an even more remarkable conclusion (based on 258 projects in 20 countries) with an average cost escalation of 45% for rail and 20% for roads. Lichtenberg (2016) documented that some projects in Denmark had overruns of almost 80%, while Odeck (2004) showed a range of overruns in Norway varying from 59% to 183%. Estimates of the cost of future investment in road infrastructure are a large area within the literature and have been addressed in a range of surveys highlighting inaccuracies in the estimation of these costs as the most significant risk in infrastructure construction, including the estimates of future material price changes (Makovšek, 2014).

Some economic studies focusing on transport infrastructure investment have conducted life cycle analysis of road infrastructure (Bessarabov et al., 2021; Cavalieri et al., 2019; Shani et al., 2021). Butt et al. (2014) found that asphalt production and material transport are the two processes that consume the most energy and emit the most greenhouse gases. In contrast, the technical literature discusses the use of new (Cong et al., 2015), innovative (Vlachovicova et al., 2007), copper (Raposeiras et al., 2021), and recycled materials (Salehi et al., 2021; Pasetto et al., 2021) as well as the exploration of the possibilities of producing a new generation of building materials and road surfaces (Lipina et al., 2017). The use of rejuvenators has been addressed from a technical point of view by several studies revealing and analysing the improved properties of these materials compared to conventional materials (Im et al., 2014; Lin et al., 2014). These studies have often focused on finding the optimal ratio to achieve the desired properties and an acceptable lifetime (Zaumanis et al., 2014; Taher et al., 2021) or the sustainability of a specific rejuvenator such as rubber seed oil (Saeed et al., 2021; Zhou et al., 2018).

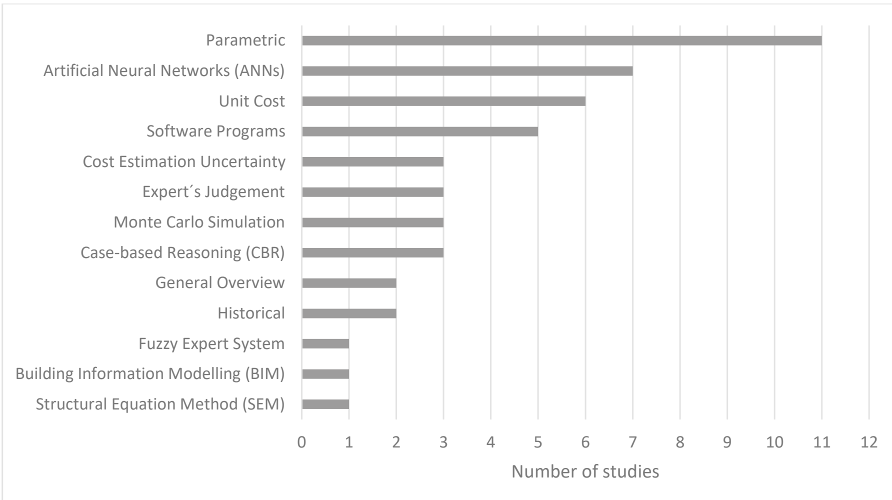
Few assessment studies on using new materials have assessed road infrastructure management's financial impacts and efficiency. Cirilovic et al. (2014) studied 14 countries in Europe and Central Asia and looked at variables that influenced the unit cost of asphalt concrete (AC) and road rehabilitation and reconstruction (RRR) costs. Their results showed that the country's corruption level and economic environment significantly affected both costs. Ahmed et al. (2015) showed how past damage cost estimation studies on highway pavement had been plagued by several devastating limitations, ranging from the lack of appropriate data and unrealistic or impractical assumptions to inadequate consideration of criteria that influence such costs. Another study by Lee and Ibbs (2005) estimated the maximum amount of highway rehabilitation/reconstruction during various closure time frames. Regarding road infrastructure management, Tran et al. (2018) provided a categorisation of road reconstruction based on 139 project pairs with five categories: (1) new construction; (2) reconstruction; (3) resurfacing, restoration, and rehabilitation (3R) projects; (4) intelligent transportation systems (ITS)-related projects; and (5) miscellaneous construction such as pavement, cycle lanes, and landscaping. Our study focuses on optimising road infrastructure management in category three, corresponding to resurfacing, restoration, and rehabilitation.

## 2 Data and Methods

The study is based on two primary data sources. The first one is the MONITOR information portal from the Ministry of Finance of Czechia (Ministry of Finance, 2017), which is the basic database of public expenditures in Czechia, both for the state budget and state funds and for local self-government units and organisations established by them, including both regions and municipalities. Data on expenditures on road maintenance and reconstruction at the level of both cohesion regions and regions from 2008 to 2015 were drawn from this database. Cohesion regions were responsible for the redistribution of financial resources from the European Structural Funds during this period, and one of their basic agendas was the financing of road reconstruction and modernisation. To specifically identify expenditures on regional roads, we used paragraph 2212 (Ministry of Finance, 2018) in combination with operational (class 5) and capital expenditures (class 6) of the budget structure. The second data source is the Transport Yearbooks of the Ministry of Transport (2003–2016), which provide basic information on the extent and condition of transport infrastructure. These yearbooks were also supplemented by information from the annual reports of the regional road infrastructure managers (officially called the given region's Road Administration and Maintenance 2003–2016). The data on geographical characteristics are based on Arc ČR 3.4 (Arc Data Praha, 2022). This dataset provides basic geographical features for Czechia in ESRI ArcGIS. Finally, our database covers 49 2nd class roads and 446 3rd class roads split into 43,262 specific sections according to road section and relevance to a municipality.

An overview of the most commonly used methods for estimating road infrastructure costs is provided by Barakchi et al. (2017). This study includes all unit cost methods corresponding with our research. Figure 1 presents the frequency of use for these methods.

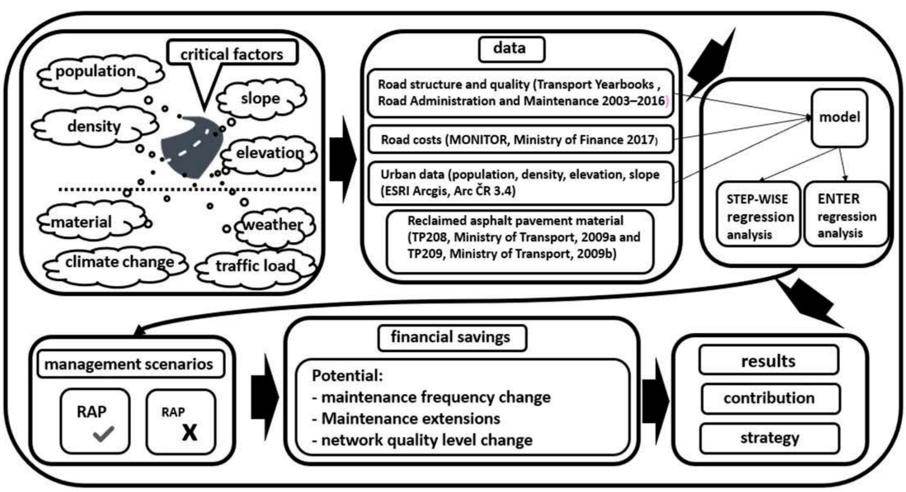
Figure 1: Cost estimation method frequency




Source: Barakchi et al. (2017).

Our study addresses the research question by looking at the management of regional road infrastructure in Czechia and identifying factors that can help answer the questions about what factors are leading to higher costs in regional road cost management. The roads in question are referred to as 2nd and 3rd class roads. These are not the most critical roads managed by the central administrator (The Road and Motorway Directorate of Czechia), but they are a very dense network of regional infrastructure managed by 14 different entities at the level of self-governing regions. These roads are managed through a road management and maintenance body subordinated to the region. This study focused only on 13 regions in Czechia because the capital of Prague is excluded from this analysis. After all, it corresponds closely to the administration of local roads. Methodologically, we start with descriptive characteristics of regional road infrastructure in Czechia, including the quality of roads. We continue defining the technological potential of using RAP material instead of conventional materials for resurfacing roads, and we assess the financial and budgetary framework of regional road investment and maintenance cost by public operational and capital expenditures. Reclaimed asphalt pavement material (RAP) is defined in this study according to official Czech technical requirements in TP208 (Ministry of Transport, 2009a) and TP209 (Ministry of Transport, 2009b). In the following part, we created a model to explain the critical regional road cost optimisation variables. All appropriate input explanatory variables were found and selected for the average total expenditure regression analysis using the step-wise regression method. These variables were then used in the classical enter regression method. Even if we studied 2010 to 2016, our analysis is based on cross-sectional data because we used whole-period averages.The period from 2010 to 2016 was selected because it corresponds with the Regional operation program funded by structural funds from the EU (officially, the period was defined from 2007 to 2013. However, the start of the disbursement was delayed by about two to three years, and it was billed financially in 2016. Long-term averages are why we have worked with raw financial expenditures, not including inflation, because the expenses for all regions correspond to cashflow volatility (see Figure 5). This method was then applied separately to capital and operational expenditures, with the sum of the regression coefficients for these two types of average expenditures always yielding a regression coefficient for total average expenses. Regression analysis is used to determine the dependence of the quantitative dependent variable under study on one or more independent quantitative variables. For all regression models, we performed residual tests: normality of distribution, autocorrelation and heteroskedasticity, specifically the Breusch-Pagan test. In cases where the models developed problems with residuals, we created new robust models using rlm functions and robust standard errors that are less prone to these problems. We then compared the results of the original and robust models. The results of the two approaches are not significantly different, and the original variables remain statistically significant. The aim of regression analysis is then to describe this dependence using an appropriate model. Finally, the study employs a scenario method, which compares two potential scenarios in terms of adaptation or resistance to the use of new materials and, based on this comparison, determines the potential cost or time savings or changes achievable in regional road management. Our methodology is reflected schematically in Figure 2.

Figure 2: Methodological framework



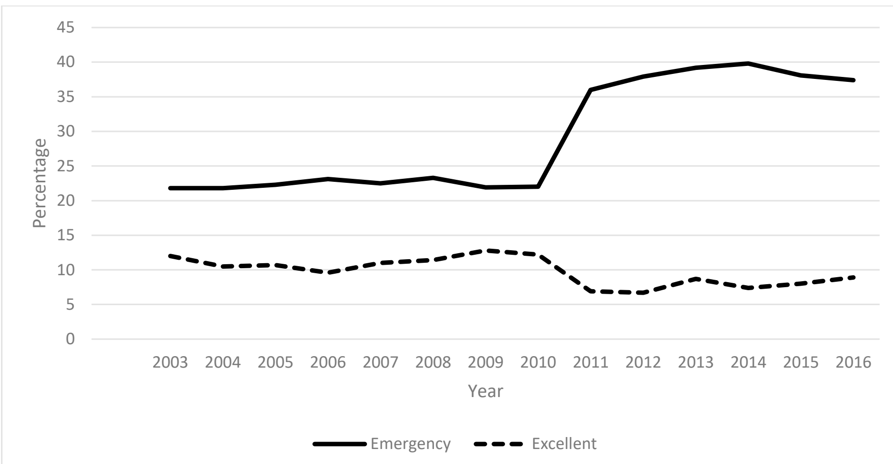

Source: authors' processing.

# 3 Results

## 3.1 Regional Road Infrastructure, Technology and Financial Framework in Czechia

In this section, we provide crucial characteristics of the regional road network in Czechia, including its geographical spread, quality level, and entry pre-conditions for using RAP material instead of conventional technology. The crucial point is identifying the needs for such repairs/modernisation/reconstruction and the follow-up technological possibilities regarding material feasibility. Figure 3 shows the average percentage of regional roads in an emergency between 2003 and 2016, according to the Catalogue of Non-rigid Road and Pavement Failures (TP82; Ministry of Transport, 2010).

Figure 3: The average share of regional roads in emergency and excellent condition according to TP82 from 2003 to 2016 (in percentage)




Source: Transport Yearbooks (Ministry of Transport, 2003–2016), Road Administration and Maintenance (2003–2016), authors' processing.

Figure 3 shows that the situation remained constant with a higher rate of roads in an emergency state, with an average during the selected period of 29%, and, in contrast, roads in an excellent state with an average of less than 10%. After 2010, the percentage of roads in an emergency state substantially increased. This could be one of the more long-term effects of the financial crisis in 2008 and 2009, given that in Czechia, there were many budgetary restrictions on the national and regional levels. While before 2010, the average share of roads in an emergency state ranged around 22%, after 2011, the average share increased to 38%.

Table 1 shows the length of roads in an emergency state, including the average annual increase in roads in an emergency state. The table presents two basic variants of the calculations. The length of roads in a state of emergency expresses the need in its maximum variant. In other words, how many kilometres of regional roads need to be repaired in the regions in total? The second variant is relatively minimal and works with the need to restore at least an annual increment of the roads in an emergency condition and bring them to excellent condition (in reality, however, more should be repaired).

Table 1: The length of roads in an emergency state (maximum variant) and the average annual increase of roads in an emergency state (minimum variant) from 2003 to 2016 (in km).

| Region | Total | Length of roads in an emergency state | Increase of roads in an emergency state |
|---|---:|---:|---:|
| Prague | 74 | 28 | 0.884 |
| Central Bohemia | 9,441 | 3,531 | 113.294 |
| South Bohemia | 6,106 | 2,284 | 73.271 |
| Plzeň | 5,024 | 1,879 | 60.283 |
| Karlovy Vary | 2,049 | 766 | 24.585 |
| Ústí nad Labem | 4,159 | 1,555 | 49.904 |
| Liberec | 2,422 | 906 | 29.068 |
| Hradec Králové | 3,742 | 1,400 | 44.909 |
| Pardubice | 3,589 | 1,342 | 43.069 |
| Vysočina | 4,981 | 1,863 | 59.775 |
| South Moravia | 4,316 | 1,614 | 51.79 |
| Olomouc | 3,533 | 1,321 | 42.396 |
| Zlín | 2,125 | 795 | 25.497 |
| Moravia-Silesia | 3,401 | 1,272 | 40.813 |

Source: Transport Yearbooks (Ministry of Transport, 2003–2016), Road Administration and Maintenance (2003–2016), authors' processing.

Table 2 shows the material distribution of the different road layers, from which the needs and possibilities for using RAP in combination with a rejuvenator are then derived, which is reflected in Table 3, which gives the unit prices of materials in EUR per tonne.

Table 2: The thickness of individual road layers and the possible use of RAP according to the ČSN EN 13108-1 standard.

| Road composition | Thickness (m) | RAP content (%) |
|---|---|---|
| Wearing course | 0.04 | 30% |
| Binder course | 0.06 | 50% |
| Base course | 0.05 | 60% |

Source: ČSN EN 13108-1 (2008); ČSN EN 13108-1 ED.2. (2017)

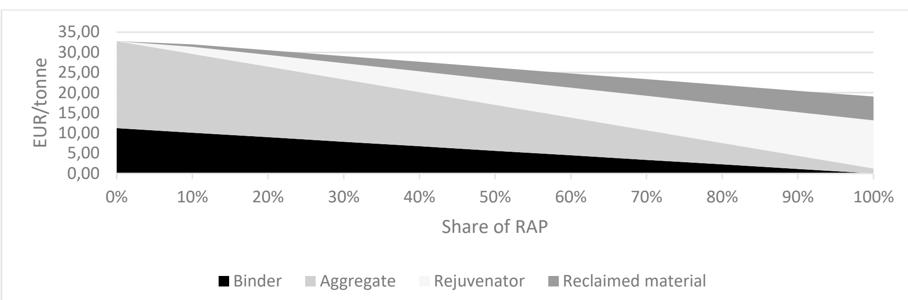
Table 3: Material prices in mixture content in 2017

| Raw material | EUR / tonne |
|---|---|
| Aggregate | 11.49 |
| Asphalt binder | 267.99 |
| Reclaimed asphalt pavement material (RAP) | 4.59 |
| Revitalising additive (rejuvenator) | 1,378.25 |

Source: ČSN EN 13108-1 (2008); ČSN EN 13108-1 ED.2. (2017)

In terms of the specific technical options for the use of RAP and the impact of the chosen process on the final cost or price, the price of the mixture can be observed to decrease with a higher ratio or quantity of RAP used, including the rejuvenator, as shown in Figure 4.

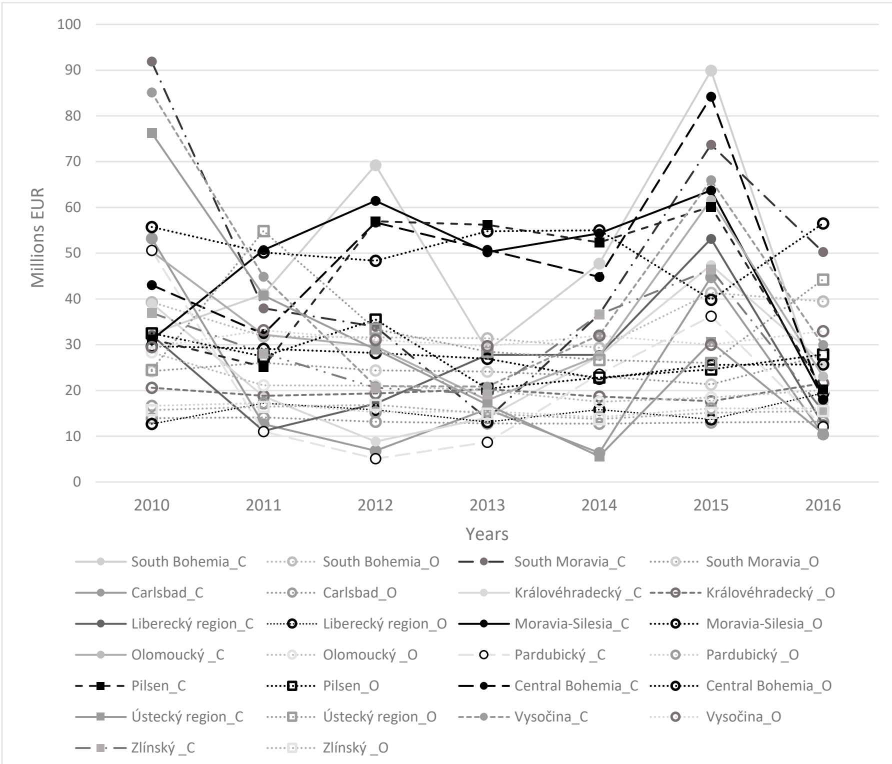
Figure 4: Relationship between the use of RAP (share in the mixture) and price (EUR/t)




Source: Koudelka, 2017.

Identifying annual regional budgetary limits is necessary to determine potential savings. It is required to consider all regional expenses and the relevant expenditures from the regional operational programmes implemented through cohesion regions from 2007 to 2016 to reflect all available funds for the financing of the repair, modernisation, or reconstruction of regional roads.

Figure 5: Total operational and capital expenditure on 2nd and 3rd class regional roads during 2010–2016 (paragraph 2212; in EUR)




Source: Ministry of Finance (2017, 2018); authors' processing
Note: C is for capital expenditures, O is for operational expenditures.

Figure 5 shows the financial budgets for regional roads, including all possible funds from both self-governing and cohesion regions. They show operational expenses and capital expenses. Total expenditures include relatively stable operational spending and, on the other hand, significantly varying capital expenditures. The seven-year average spending over the reference period is assessed as relevant according to a further procedure for evaluating the annual market potential for road repairing activities. Because capital expenditures on regional roads vary significantly in individual years, these fluctuations during this period were mainly caused by the drawing of EU structural funds implemented by the regional operational programmes for each cohesion region. This fact was reflected very clearly in 2015.

## 3.2 The Model of Road Cost Management Factors

This section defines the model to identify road cost management as a crucial factor. In our defined model, the three explanatory variables, total, capital and operating expenditure on regional roads, were successively considered in the STEP-WISE and ENTER regression analysis. Step-wise regression is a method of finding the best predictive model. The variables enter the model sequentially in a specific order. At each step, all predictors are examined to determine which one best captures the variability of the dependent variable and its inclusion in the model is decided using sequential F-tests. When the proportion of explained variability increases, the variable is included, a rough rule of thumb for this method is that in a regression based on STEP-WISE, there should be at least forty cases for each variable, so the model should satisfy the 1:40 ratio of the number of variables to the number of observations. Once all variables are selected for the model, the parameters of the linear regression function are estimated, and the regression quality is assessed using the index of determination R2, which indicates the proportion of variability explained by the model. This is identical to the classical ENTER regression method, where only all the variables suitably selected in advance are entered into the model. Unless the analysis aims to fit an overall model that thoroughly explains the phenomenon under study, only t-tests of individual variables are essential. Suppose their P-value of significance is less than the significance level (usually 0.05). In that case, the variable is statistically significant in the model, and the magnitude of the effect on the explained variable is given directly by the regression coefficient, which tells how many units the explained variable changes if the input variable increases by one unit.

We analysed the following variables included in our model: road_class defines the type and the level of the road, it divides the sample into 2nd class roads and 3rd class roads, which are the categories managed on the regional level in Czechia; road_length defines the length of road in one municipal cadastral area in meters; age_days this variable describes the age of road expressed in days; slope_mean corresponds with mean slope of the road according to the geographical area; elevation_mean corresponds with the mean elevation of the road according to the geographical area; area_ha corresponds with the area covered by the road in the relevant municipal cadastral area; pop1961 is municipality population in 1961 relevant to the selected section of the road; pop2011 is municipality population in 2011 relevant to the selected section of the road; density2011 is population density of municipality in 2011 relevant to selected section of the road; change1971 is population density change in municipality between 1961 census and 1971 census relevant to the selected section of the road; change1981 is population density change in municipality between 1971 census and 1981 census relevant to the selected section of the road; change1991 is population density change in municipality between 1981 census and 1991 census relevant to the selected section of the road; change2001 population density change in municipality between 1991 census and 2001 census relevant to the selected section of the road; change2011 is population density change in municipality between 2001 census and 2011 census relevant to the selected section of the road.

The regression model found for total average expenditure (Table 4) explains 15% of the total variability according to the R2 determination index. This is not much, but the analysis aimed not to find a comprehensive model but to find which variables affect the level of expenditure. Moreover, the model achieved a good quality level because the significance of the P-value of the overall F-test on the model was less than 0.05. The histogram of the model's residuals shows a mean of 1 and a standard deviation of 0, indicating a good-quality model. All the selected input variables are statistically significant in the model because the significance P-value of the t-test was less than 0.05. Their regression coefficients then form the equation of the resulting total expenditure model.

Table 4: Model on total expenditures

| | **Unstandardised Coefficients** | | **Standardised Coefficients** | | |
|---|---|---|---|---|---|
| **Variable** | **B** | **Std. Error** | **Beta** | **t** | **Sig.** |
| (Constant) | 426.330 | 3.057 | | 139.470 | .000 |
| road_class | 8.888 | 1.148 | .039 | 7.741 | .000 |
| road_length | .003 | .000 | .028 | 6.253 | .000 |
| age_days | -1.475 | .062 | -.120 | -23.936 | .000 |
| slope_mean | 2.562 | .261 | .056 | 9.800 | .000 |
| elevation_mean | -.037 | .003 | -.068 | -11.857 | .000 |
| area_ha | .005 | .000 | .176 | 17.403 | .000 |
| pop1961 | -.009 | .000 | -5.569 | -42.066 | .000 |
| pop2011 | .008 | .000 | 5.450 | 40.106 | .000 |
| density2011 | .012 | .003 | .096 | 4.915 | .000 |
| change1971 | .111 | .025 | .075 | 4.528 | .000 |
| change1981 | -.372 | .021 | -.132 | -18.013 | .000 |
| change1991 | -.492 | .027 | -.158 | -18.326 | .000 |
| change2001 | .805 | .039 | .307 | 20.719 | .000 |
| change2011 | -1.051 | .023 | -.246 | -45.722 | .000 |

Source: authors' processing

The constant for total average expenditure is 426.33. The regression coefficient for road class indicates that if the road is 3rd class and not 2nd class, the total average expenditure is higher by 8.888. This result corresponds with the continuous connectivity of 2nd class roads, which creates a constant network while the 3rd class roads are not connected. In other words, inter-connected networks are less expensive to maintain or invest in. If the length of the measured section is greater by one, then expenditures are increasing by 0.003. If the road age exceeds one, expenditures are lower by 1.475. This result is very logical and intuitive: the older the road, the higher the costs of maintenance or modernisation. If the slope is greater than one, then expenditures are more significant by 2.562. Even in this case, the slope and geographical conditions matter, which is also confirmed in the case of elevation. If the average elevation exceeds one, expenditures are lower by 0.037. If the area is higher by one hectare, the expenditure is higher by 0.005. If the 1961 population was more significant by one, expenditures are lower by 0.009, and if the 2011 Census population is more significant by one, expenditures are higher by 0.008. If the 2011 density is greater by one, expenditures are higher by 0.012. Changes in population densities between censuses affect spending levels but differ each decade. A change in 1971 density more significant than one means spending is 0.111 higher, a change in 1981 density more significant than one means spending is 0.372 lower, a change in 1991 means spending is 0.492 lower, a change in 2001 means spending is 0.805 higher, and a change in 2011 means spending is 1.051 lower. Taken together across all decades, an average density change that is more significant than one means a reduction in total average spending of 0.987.

The regression model of average capital expenditure (Table 5) explains 12.8% of the total variability according to the R2 determination index. This is not much, but the goal of the analysis was not to find a comprehensive model but to find which variables affect the level of spending. The model is again of good quality. The P-value of the significance of the overall F-test on the model came out to less than 0.05. The histogram of the model's residuals shows a mean of 1 and a standard deviation of 0, indicating a good-quality model. All but one of the selected input variables (mean elevation) are statistically significant in the model, as the P-value of the significance of the t-test came out to less than 0.05 for all of them. Their regression coefficients then form the equation of the resulting total expenditure model.

The constant for average capital expenditure is 245.562. The regression coefficient for road class indicates that if the road is 3rd class and not 2nd class, the average capital expenditure is 5.115 higher. If the length of the measured section is greater by one, then expenditures are more significant by 0.003. If the road age is more significant than one, expenditures are lower by 1.082. If the slope is greater than one, expenditures are more significant by 2.066. If the average elevation is greater than one, expenditures are lower by 0.001, which does not have a significant effect, so this variable came out statistically insignificant for the model. If the area is higher by one ha, expenditures are higher by 0.003. If the 1961 population was more significant by one, expenditures are lower by 0.006; if the 2011 census population is more significant by one, expenditures are higher by 0.006. If the 2011 density is greater by one, expenditures are higher by 0.006. Changes in population densities between censuses affect spending levels but differ each decade. A 1971 density change more remarkable than one means higher expenditures by 0.119, a 1981 density change more remarkable than one implies a decrease in expenditures by

0.279, a 1991 density change represents a decline in expenditures by 0.299, a 2001 density change means an increase of 0.554, and a 2011 density change implies a decrease in expenditures by 0.814. In sum, across all decades, an average density change that is more remarkable than one means reducing capital average expenditures by 0.712.

Table 5: Model on capital expenditures

| | Unstandardised Coefficients | | Standardised Coefficients | | |
|---|---|---|---|---|---|
| **Variable** | **B** | **Std. Error** | **Beta** | **t** | **Sig.** |
| (Constant) | 245.562 | 2.409 | | 101.945 | .000 |
| road_class | 5.115 | .905 | .028 | 5.653 | .000 |
| road_length | .003 | .000 | .035 | 7.526 | .000 |
| age_days | -1.082 | .049 | -.113 | -22.291 | .000 |
| slope_mean | 2.066 | .206 | .058 | 10.029 | .000 |
| elevation_ mean | -.001 | .002 | -.001 | -.232 | .816 |
| area_ha | .003 | .000 | .140 | 13.664 | .000 |
| pop1961 | -.006 | .000 | -4.969 | -37.054 | .000 |
| pop2011 | .006 | .000 | 4.918 | 35.731 | .000 |
| density2011 | .006 | .002 | .059 | 3.020 | .003 |
| change1971 | .119 | .019 | .103 | 6.153 | .000 |
| change1981 | -.279 | .016 | -.127 | -17.132 | .000 |
| change1991 | -.299 | .021 | -.123 | -14.126 | .000 |
| change2001 | .554 | .031 | .272 | 18.099 | .000 |
| change2011 | -.814 | .018 | -.245 | -44.928 | .000 |

Source: authors' processing

The regression model found for operating average expenditures (Table 6) explains 18.3% of the total variability according to the R2 determination index. This is not much, but the analysis aimed not to find a comprehensive model but to find which variables affect the level of expenditure. The P-value of the significance of the overall F-test on the model is again less than 0.05. The histogram of the model's residuals shows a mean of 1 and a standard deviation of 0, indicating a good-quality model. All but two of the selected input variables (length of the measured segment and change in density 1971) are statistically significant in the model, as the P-value of the significance of the t-test came out less than 0.05 for all of them. Their regression coefficients then form the equation of the resulting total expenditure model. The constant for the operating average expenditure is 180.768. The regression coefficient for road class indicates that if the road is 3rd class and not 2nd class, the average running expenditure is higher by 3.774. This result confirms the significance of the network connectivity and its impact on the spending.

Table 6: Model on operational expenditures

| | Unstandardised Coefficients | | Standardised Coefficients | | |
|---|---|---|---|---|---|
| **Variable** | **B** | **Std. Error** | **Beta** | **t** | **Sig.** |
| (Constant) | 180.768 | .927 | | 194.909 | .000 |
| road_class | 3.774 | .348 | .053 | 10.833 | .000 |
| road_length | .000 | .000 | .005 | 1.062 | .288 |
| age_days | -.392 | .019 | -.103 | -20.996 | .000 |
| slope_mean | .496 | .079 | .035 | 6.253 | .000 |
| elevation_mean | -.037 | .001 | -.217 | -38.476 | .000 |
| area_ha | .002 | .000 | .217 | 21.870 | .000 |
| pop1961 | -.003 | .000 | -5.505 | -42.409 | .000 |
| pop2011 | .002 | .000 | 5.248 | 39.385 | .000 |
| density2011 | .006 | .001 | .159 | 8.356 | .000 |
| change1971 | -.008 | .007 | -.017 | -1.057 | .290 |
| change1981 | -.093 | .006 | -.107 | -14.871 | .000 |
| change1991 | -.193 | .008 | -.200 | -23.712 | .000 |
| change2001 | .251 | .012 | .309 | 21.280 | .000 |
| change2011 | -.237 | .007 | -.179 | -34.008 | .000 |

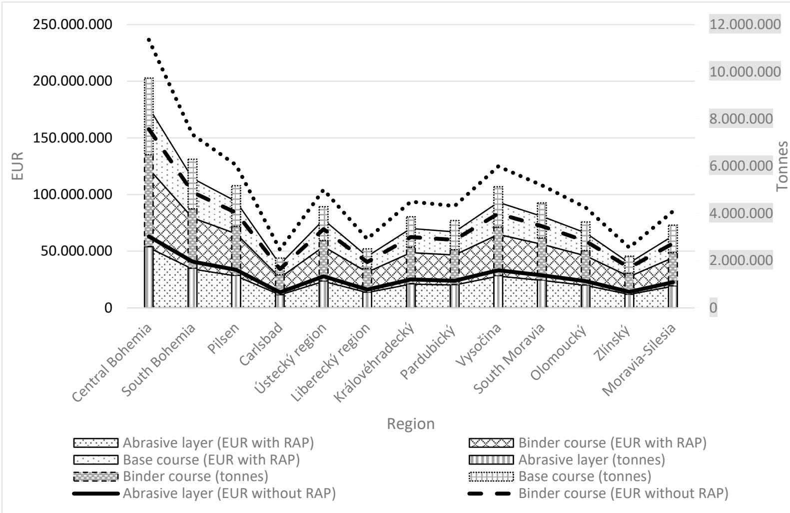
Source: authors' processing

If the length of the measured section is greater by one, then expenditure does not change (0.000), so this variable came out statistically insignificant for the model. If the road age exceeds one, expenditures are lower by 0.392. If the slope is more significant than one, then expenditures are higher by 0.496. These results confirm the importance of geographical conditions, even confirmed by the elevation. If the average elevation exceeds one, expenditures are lower by 0.037. If the area is higher by one hectare, the spending is higher by 0.002. If the 1961 population was more significant by one, expenditures are lower by 0.003; if the 2011 Census population is more significant by one, expenditures are higher by 0.002. If the 2011 density is greater by one, expenditures are higher by 0.006. Changes in population densities between censuses affect spending levels, but each decade differs. A change in 1971 density higher by one means spending is lower by 0.008, which does not have a significant effect, so this variable came out statistically insignificant for the model. A change in 1981 density more remarkable than one means a 0.093 decrease in spending, a change in 1991 represents a 0.193 decrease in spending, a change in 2001 means a 0.251 increase in spending, and a change in 2011 means a 0.237 decrease in spending. Taken together across all decades, an average density change more remarkable than one implies a 0.274 reduction in average operating expenditures.

## 3.3 Road Cost Management Scenarios

Under the aforementioned assumptions regarding the utilisation of RAP, the total expenditures required for the repair, modernisation, or reconstruction of regional roads were calculated according to the individual variants based on Table 1. The necessary material was calculated by recalculating the total monetary value in EUR. These calculations were considered for a road width of 7.5 m, which meets the Czech standard (TP82; Ministry of Transport, 2010). Both calculation variants shown in Figures 6 and 7 always reflected the material requirement and its price without RAP compared to the price with RAP. In both cases, the distribution of material and prices for the individual layers, including abrasive, binder, base, and total sum. It can be seen from the figures that to consistently place all 2nd and 3rd class regional roads in an emergency state into an excellent state (the maximum variant), it would be necessary with existing technology to pay for all regions excluding the capital city of Prague a total of EUR 1.378 billion. At the same time, only EUR 1.026 billion would be needed with the use of RAP. Thus, the price difference is EUR 352 million (25.5%), the savings achieved in regional budgets using this material. On the other hand, it is possible to see the entire problem oppositely. Benefits other than only financial savings can be considered because, with the preserved expenditures in this necessary amount of EUR 1.378 billion, it would be possible to repair longer sections in a poor condition: not only roads in an emergency state but also roads and parts of roads in a non-compliant state (TP82 – 4). This would be done by utilising the aforementioned 25% savings on repairs of roads in an emergency state.

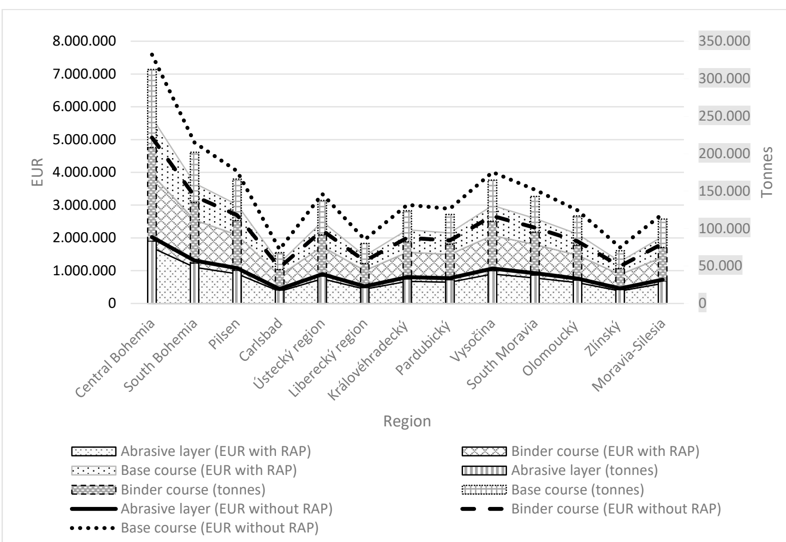
Figure 6: Maximum variant – What likely needs to be repaired by region?




Source: authors' processing

In the minimal variant represented in Figure 7, which is based on the necessity to carry out repairs on at least such a length of roads that is equal to the average annual increase in roads in an emergency state from 2003 to 2016, only 1.2% of all roads are considered, which equals 659 km. With this minimal variant, the costs with current technology correspond to EUR 44.14 million, whereas the expenses with RAP total about EUR 32.963 million, revealing savings of EUR 11.179 million.

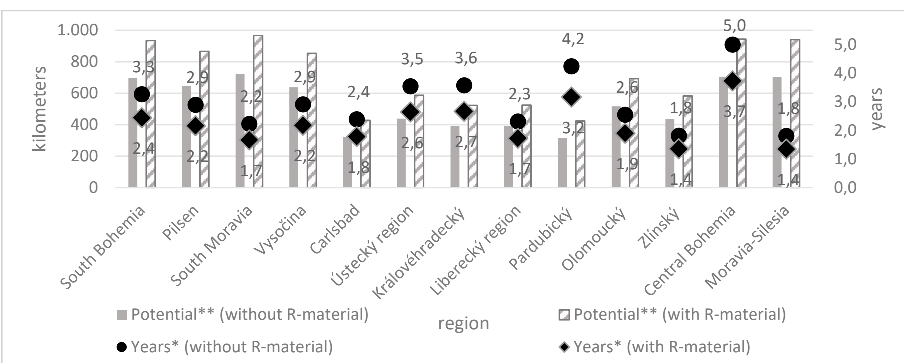
Figure 7: Minimum variant – What necessarily needs to be repaired by region?




Source: authors' processing

We define scenarios A and B. Annex 1 shows the annual average capital expenditures in the individual regions and their total for the Czech Republic. The table then identifies the time needed to reconstruct all roads in an emergency state and the potential length of roads that could be reconstructed in one financial year. Everything was calculated in Scenario A without the use of RAP. Annexe 2 shows the possible savings in EUR and the time needed to reconstruct all roads in the emergency state or the potential length of the roads, which can be reconstructed in one budget year in Scenario B using RAP. Figure 8 compares the scenarios with and without RAP, with the characteristics identified in Annexes 1 and 2 (the number of years required to reconstruct roads in an emergency state and the potential for road repairs in km). It is clear from these results that the market for road maintenance and management of 2nd and 3rd class roads in terms of RAP use during reconstruction ranges around the long-term average of approximately EUR 459 mil per year for all regions excluding Prague (see Annex 1). Another finding is that, from the point of view of road controllers, it is possible to reduce the average time for the reconstruction of all roads in an emergency state (with the maximum utilisation of investment expenditures) from 3 years to about 2 years using RAP see Fig. 6), thus shortening this interval by about one third (on average for the regions considered). Another determined fact is that using all of the funds saved, not only could nearly 7,000 km of roads per year be repaired without RAP (see Annexe 1), but 9,000 km of roads could be repaired with it (see Annexe 2). With a total length of regional roads of 54,888 km (excluding Prague), it is theoretically possible to reduce the period for reconstructing the complete network from 8 years to 6 (assuming full utilisation of investment expenditures from regional budgets and the budgets of the regional councils of cohesion regions according to paragraph 2212 (Ministry of Finance, 2018) of the sectoral division of local self-government budgets and organisations).

Figure 8: The time needed to restore all regional roads in an emergency state (in years) and the potential for annual repairs using RAP (in km)




Source: authors' processing

Table 7 shows the possible savings available for the minimum variant, namely for reconstructing only such a length of roads that corresponds to the yearly increase in the length of roads in an emergency state, which would not, in the long-term, lead to the overall improvement in the state of the entire network of regional roads. It is, of course, advisable to carry out some repairs in advance when the roads are not yet in a state of emergency (only in, for example, a state of non-compliance).

Table 7: Identification of the potential savings in the minimal variant

| Region | Annual average capital expenditure (in EUR) | EUR without Rm | EUR with Rm | Potential savings (EUR) |
|---|---|---|---|---|
| South Bohemia | 46,814,510 | 4,909,571 | 3,666,329 | 1,243,243 |
| Pilsen | 43,373,790 | 4,039,311 | 3,016,443 | 1,022,868 |
| South Moravia | 48,389,195 | 3,470,261 | 2,591,493 | 878,769 |
| Vysočina | 42,758,088 | 4,005,305 | 2,991,048 | 1,014,257 |
| Carlsbad | 21,459,804 | 1,647,361 | 1,230,203 | 417,159 |
| Ústecký | 29,400,774 | 3,343,882 | 2,497,116 | 846,766 |
| Královéhradecký | 26,201,070 | 3,009,205 | 2,247,189 | 762,016 |
| Liberecký | 26,221,756 | 1,947,706 | 1,454,492 | 493,214 |
| Pardubický | 21,178,232 | 2,885,865 | 2,155,082 | 730,783 |
| Olomoucký | 34,694,528 | 2,840,776 | 2,121,411 | 719,365 |
| Zlínský | 29,200,883 | 1,708,471 | 1,275,838 | 432,633 |
| Central Bohemia | 47,280,490 | 7,591,407 | 5,669,047 | 1,922,359 |
| Moravia-Silesia | 47,093,661 | 2,734,710 | 2,042,204 | 692,506 |
| **Total** | **464,066,782** | **44,133,832** | **32,957,895** | **11,175,937** |

Source: authors' processing

## 4 Discussion

Our analysis reveals several interesting findings regarding critical factors that may influence the cost of regional road management in the long run. Road type appears to be the most significant factor in increasing average total, capital and operating expenditures. However, it is somewhat surprising that a 3rd class road is relatively more expensive than a 2nd class road (of higher hierarchical importance) in terms of investment and maintenance.

This finding is contrary to expectations. However, it can be interpreted precisely by the fragmented and geographically inconsistent network of 3rd class roads. In contrast, 2nd class roads are primarily long and interconnected sections forming a continuous network. The disruption of this continuity in the case of 3rd class roads leads to their being managed in smaller sections and makes investment and maintenance relatively more costly. In other words, some economies of scale can be achieved for 2nd class roads. The slope of the terrain where the road is built and subsequently managed is also proving to be critically important. This geographical assumption significantly affects the increase in average investment costs, but it also increases the cost of routine maintenance to a lesser extent. Demographic factors show another interesting finding: neither population nor population density significantly affects regional road management costs. On the contrary, the change in population density plays a role. Again, contrary to the assumptions, an increase in population density does not increase the cost of road management, which might be expected since a more significant population adjacent to a given section implies a higher traffic volume. Nevertheless, the effect is the opposite. It can be explained by the fact that when new residential districts adjacent to the regional road are built, the management of the road is transferred from the region to the municipality. Thus, the road is moved under the municipality's management in the long term. This process then leads to a reduction in expenditure at the regional level.

In our analysis, we considered the period from 2010 to 2016. This period (following the financial crisis starting in 2008) was very stable in Czechia in terms of monetary issues. The gross domestic product deflator yearly change was less than 1%, and the consumer price index annual change achieved around 1.5%. Moreover, the construction output price index showed a decrease in the construction area (Czech Statistical Office, 2023). Thus, the time-given price issues do not significantly affect the relevant period. On the other hand, the last few, starting in 2020 with the COVID-19 crisis, showed a high risk of price volatility of material inputs determined by global supply chain disruptions. The construction output price index in November 2022 achieved almost 12% (Czech Statistical Office, 2023), which means a significant change compared to the studied period. It defines the limit of our study and emphasises the factor of time as a very considerable feature that needs to be considered in road maintenance planning. The savings regarding the costs of RAP can still be identified compared to conventional mixes. The combined savings of asphalt binder and aggregate from using RAP and RAS in asphalt mixtures in the United States is estimated at more than $3.0 billion and nearly 59 million cubic yards of landfill space (Williams et al., 2020).

The presented results' predictive ability is limited by the use of existing technologies used in Czechia for the maintenance and repair of regional roads. At the same time, these results are limited by the potential use of RAP and its specific ratio together with a rejuvenator. The critical limitation of our results lies in discussing the RAP mixture. Based on annual industry and highway agency surveys in the United States, there appears to be an upper limit on the average amount of RAP in asphalt mixtures of about 20%. However, these same surveys have identified that most state Department of Transportation (DOT) specifications and standards will allow up to 30% RAP on average (Copeland, 2011; Hansen & Copeland, 2015). Nevertheless, the average percentage of RAP used in asphalt mixtures in the United States has increased from 15.6 per cent in 2009 to 21.3 per cent in 2020. On the contrary, in Japan, RAP used in asphalt pavements achieves, on average, 47 per cent (Williams et al., 2020). Thus, the potential scenario savings can vary according to the specific mixtures implemented in road maintenance.

## 5 Conclusion

In conclusion, we studied road cost optimisation factors using the example of Czech regional road networks. The regional road level is rarely discussed in current literature compared to primarily studied highways or local roads. Our study focused on urban factors affecting road maintenance costs, especially network structure and discontinuity, slope, elevation, population and density, and long-term changes. According to our results, the critical factors that increase road costs are slope (increasing the costs by more than two times) and the discontinuity of the network represented by road class, which can increase the costs most significantly. On the contrary, the population and density are not very significant factors in a long-term period, which is an unexpected result. Then, we defined road maintenance scenarios that distinguished the usage of RAP to identify potential financial savings. From the above results, it is clear that to consistently place all 2nd and 3rd class regional roads currently in an emergency state into an excellent state as in the maximum variant, it would be necessary to pay for all regions excluding Prague with conventional mixes of the total of about EUR 1.378 billion, while when using RAP only EUR 1.026 billion would be needed. Thus, the price difference is EUR 352 million (25.5%), which determines the total savings.

Furthermore, the results show that, in terms of the use of RAP during reconstruction, the market potential in the administration sector, using all capital expenditures of regions and cohesion regions in paragraph 2212 (Ministry of Finance, 2018) of the sectoral division of 2nd and 3rd class roads, ranges around the long-term average of about EUR 464 million in total for all regions excluding Prague (see Annex 1). This figure is the maximum possible potential, which means it is possible to reduce the average time for reconstructing all roads in an emergency state from 3 years to about 2 years using RAP, thus shortening this interval by about one-third. When considering the overall length of the regional roads of 54,888 km (excluding Prague), in the maximalist variant, it would be theoretically possible to reduce the period for reconstructing the complete network from 8 years to 6 (assuming the full utilisation of the investment expenditures from the regional budgets. Nevertheless, the interval can be shortened by about one quarter, ultimately improving the state of the entire network of regional roads.

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## References

Abeysekara, B. et al. (2021). Improving the capital deployment efficiency: An infrastructure investment planning process in transportation project. Research in Transportation Economics, 88, pp. 1–17. https://doi.org/10.1016/j.retrec.2021.101048.

Ahmed, A., Bai, Q. and Labi, S. (2015). Pavement damage cost estimation: a synthesis of past research. Proceedings of the Institution of Civil Engineers – Transport, 168 (1), pp. 48–58. https://doi.org/10.1680/tran.12.00075.

Arc Data Praha. (2022). Arc ČR 3.4. At <https://www.arcdata.cz/produkty/geograficka-data/arccr-4>, accessed 22 January 2022.

Barakchi, M., Torp, O. and Belay, A. M. (2017). Cost estimation methods for transport infrastructure: A systematic literature review. Procedia Engineering, 196, pp. 270–277. https://doi.org/10.1016/j.proeng.2017.07.199.

Bessarabov, A., Priorov, G. and Glushko, A. (2021). The life cycle of the development of road impregnations for motor transport infrastructure. Energy Reports, 7, pp. 8633–8638. https://doi.org/10.1016/j.egyr.2021.03.045.

Butt, A. A. et al. (2014). Life cycle assessment framework for asphalt pavements: Methods to calculate and allocate energy of binder and additives. International Journal of Pavement Engineering, 15(4), pp. 290–302. https://doi.org/10.1080/10298436.2012.718348.

Cantarelli, C. C., Flyvbjerg, B. and Buhl, S. L. (2012a). Geographical variation in project cost performance: The Netherlands versus worldwide. Journal of Transport Geography, 24, pp. 324–331. https://doi.org/10.1016/j.jtrangeo.2012.03.014.

Cantarelli, C. C. et al. (2012b). Different cost performance: different determinants? The case of cost overruns in Dutch transport infrastructure projects. Transport Policy, 22, pp. 88–95. https://doi.org/10.1016/j.tranpol.2012.04.002.

Cavalieri, M., Cristaudo, R. and Guccio, C. (2019). On the magnitude of cost overruns throughout the project life-cycle: An assessment for the Italian transport infrastructure projects. Transport Policy, 79, pp. 21–36. https://doi.org/10.1016/j.tranpol.2019.04.001.

Cechet, B. (2005). Climate change impact on the pavement maintenance and rehabilitation costs associated with the Australian National Highway Network. In MODSIM 2005, International Congress on Modelling and Simulation, pp. 489–496.

Celauro, C. et al. (2017). Environmental analysis of different construction techniques and maintenance activities for a typical local road. Journal of cleaner production, 142, pp. 3482–3489. https://doi.org/10.1016/j.jclepro.2016.10.119.

Chang, A. S. T. (2002). Reasons for cost and schedule increase for engineering design projects. Journal of Management in Engineering, 18 (1), pp. 29–36. https://doi.org/10.1061/(ASCE)0742-597X(2002)18:1(29).

Cirilovic, J. et al. (2014). Developing cost estimation models for road rehabilitation and reconstruction: Case study of projects in Europe and Central Asia. Journal of Construction Engineering and Management, 140(3), pp. 1–25. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000817.

Cong, P. et al. (2015). Investigation on recycling of SBS modified asphalt binders containing fresh asphalt and rejuvenating agents. Construction and Building Materials, 91, pp. 225–231. https://doi.org/10.1016/j.conbuildmat.2015.05.041.

Copeland, A. (2011). Reclaimed asphalt pavement in asphalt mixtures: State of the practice (No. FHWA-HRT-11-021). United States: Federal Highway Administration. Office of Research, Development, and Technology.

ČSN EN 13108-1. (2008). Czech Technical Standard. Bituminous mixtures – Material specifications - Part 1: Asphalt concrete.

ČSN EN 13108-1 ED.2. (2017). Czech Technical Standard. Bituminous mixtures – Material specifications - Part 1: Asphalt concrete.

Czech Statistical Office. (2023). Hlavní makroekonomické ukazatele [Key macroeconomic indicators]. At <https://www.czso.cz/csu/czso/hmu_cr>, accessed 12 January 2023.

Flyvbjerg, B., Skamris Holm, M. K. and Buhl S. L. (2003). How common and how large are cost overruns in transport infrastructure projects? Transport Reviews, 23(1), pp. 71–88. https://doi.org/10.1080/01441640309904.

Hansen, K. R. and Copeland, A. (2015). Asphalt pavement industry survey on recycled materials and warm-mix asphalt usage: 2014 (No. Information Series 138). Washington: Federal Highway Administration.

Haraldsson, M. (2007). Marginal costs for road maintenance and operation: a cost function approach. Working Papers, 7, Stockholm: Swedish National Road & Transport Research Institute (VTI).

Henning, T. F. et al. (2014). Relationship between traffic loading and environmental factors and low-volume road deterioration. Transportation Research Record, 2433(1), pp. 100–107. https://doi.org/10.3141/2433-11.

Im, S. et al, (2014). Impacts of rejuvenators on performance and engineering properties of asphalt mixtures containing recycled materials. Construction and Building Materials, 53, pp. 596–603. https://doi.org/10.1016/j.conbuildmat.2013.12.025.

Koudelka, T. (2017). Vliv různých druhů rejuvenátorů na vlastnosti asfaltového pojiva. In Sborník abstraktů Juniorstav. Brno: Brno University of Technology.

Lee, E. B. and Ibbs, C. W. (2005). Computer simulation model: Construction analysis for pavement rehabilitation strategies. Journal of Construction Engineering and Management -ASCE, 131 (4), pp. 449–458. https://doi.org/10.1061/(ASCE)0733-9364(2005)131:4(449).

Lichtenberg, S. (2016). Successful control of major project budgets. Administrative Sciences, 6(3), p. 8. https://doi.org/10.3390/admsci6030008.

Lin, J. et al. (2014). Effectiveness of rejuvenator seal materials on performance of asphalt pavement. Construction and Building Materials, 55, pp. 63–68. https://doi.org/10.1016/j.conbuildmat.2014.01.018.

Lipina, S. A., Zaikov, K. S. and Lipina, A. V. (2017). Introduction of innovation technology as a factor in environmental modernisation in Russian Arctic. Economic and Social Changes: Facts Trends Forecast, 50 (2), pp. 164–180. https://doi.org/ 10.15838/esc/2017.2.50.9.

Makovšek, D. (2014). Systematic construction risk, cost estimation mechanism and unit price movements. Transport Policy, 35, pp. 135–145. https://doi.org/10.1016/j.tranpol.2014.04.012.

Mallick, R. B. et al. (2014). Use of system dynamics to understand long-term impact of climate change on pavement performance and maintenance cost. Transportation Research Record, 2455(1), pp. 1–9. https://doi.org/10.3141/2455-01.

Ministry of Finance. (2017). MONITOR. At <https://monitor.statnipokladna.cz/>, accessed 16 July 2021.

Ministry of Finance. (2018). Vyhláška č. 323/2002 Sb., o rozpočtové skladbě [Decree No. 323/2002 Coll., on budget structure, as amended].

Ministry of Transport. (2009a). Technické podmínky: Recyklace konstrukčních vrstev netuhých vozovek za studena (TP208) [Technical requirements: Cold recycling of non-rigid pavement layers]. At <http://www.pjpk.cz/data/USR_001_2_8_TP/TP_208.pdf>, accessed 16 July 2021 .

Ministry of Transport. (2009b). Technické podmínky: Recyklace asfaltových vrstev netuhých vozovek na místě za horka (TP209) [Technical requirements: On-site recycling of asphalt layers on unpaved roads in hot conditions]. At <https://pjpk.rsd.cz/data/USR_001_2_8_TP/TP_82.pdf>, accessed 16 July 2021.

Ministry of Transport. (2010). Technické podmínky: Katalog poruch netuhých vozovek (TP82) [Technical requirements: Catalogue of non-rigid road and pavement failures]. At <https://pjpk.rsd.cz/data/USR_001_2_8_TP/TP_82.pdf>, accessed 16 July 2021.

Ministry of Transport. (2003–2016). Transport Yearbooks. At <https://www.sydos.cz/en/yearbooks.htm>, accessed 20 July 2021.

Nassiri, S., Bayat, A. and Salimi, S. (2015). Survey of practice and literature review on municipal road winter maintenance in Canada. Journal of Cold Regions Engineering, 29 (3), p. 04014015. https://doi.org/10.1061/(ASCE)CR.1943-5495.0000082.

Nicholls, C. et al. (2016). Effect of using of reclaimed asphalt and/or lower temperature asphalt on the Availability of the Road Network. Materials and Infrastructures, 2 (5), pp. 59–73. https://doi.org/10.1002/9781119318613.ch5.

Odeck, J. (2004). Cost overruns in road construction—what are their sizes and determinants? Transport Policy, 11 (1), pp. 43–53. https://doi.org/10.1016/S0967-070X(03)00017-9.

Pais, J. C., Amorim, S. I. and Minhoto, M. J. (2013). Impact of traffic overload on road pavement performance. Journal of transportation Engineering, 139 (9), pp. 873–879. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000571.

Pasetto, M. et al. (2021). Towards very high RAP content asphalt mixes: A comprehensive performance-based study of rejuvenated binders. Journal of Traffic and Transportation Engineering, 8(6), pp. 1022–1035. https://doi.org/10.1016/j.jtte.2020.12.007.

Raposeiras, A. C. et al. (2021). Production of asphalt mixes with copper industry wastes: Use of copper slag as raw material replacement. Journal of Environmental Management, 293, p. 112867. https://doi.org/10.1016/j.jenvman.2021.112867.

Road Administration and Maintenance. (2003–2016). Information available for each region from 2003 to 2016, in some cases online from the website of the respective organisation. Czech Republic: Road and Administration and Management.

Saeed, S. M. et al. (2021). Optimisation of rubber seed oil content as bio-oil rejuvenator and total water content for cold recycled asphalt mixtures using response surface methodology. Case Studies in Construction Materials, 15, e00561. https://doi.org/10.1016/j.cscm.2021.e00561.

Salehi, S. et al. (2021). Sustainable pavement construction: A systematic literature review of environmental and economic analysis of recycled materials. Journal of Cleaner Production, 313, p. 127936. https://doi.org/10.1016/j.jclepro.2021.127936.

Shani, P., Chau, S. and Swei, O. (2021). All roads lead to sustainability: Opportunities to reduce the life-cycle cost and global warming impact of US roadways. Resources, Conservation and Recycling, 173, p. 105701. https://doi.org/10.1016/j.resconrec.2021.105701.

Stückelberger, J. A., Heinimann, H. R and Burlet, E. C. (2006). Modeling spatial variability in the life-cycle costs of low-volume forest roads. European Journal of Forest Research, 125 (4), pp. 377–390. https://doi.org/10.1007/s10342-006-0123-9.

Taher, S. F. et al. (2021). Identification of fracture parameters of fiber reinforced concrete beams made of various binders. Case Studies in Construction Materials, 15, e00573. https://doi.org/10.1016/j.cscm.2021.e00573.

Tran, D. Q., Diraviam, G. and Minchin, R. E., Jr. (2018). Performance of highway design-bid-build and design-build projects by work types. Journal of Construction Engineering and Management, 144(2). https://doi.org/10.1061/(ASCE)CO.1943-7862.0001437.

Vlachovicova, Z. et al. (2007). Creep characteristics of asphalt modified by radial styrene–butadiene–styrene copolymer. Construction and Building Materials, 21(3), pp. 567–577. https://doi.org/10.1016/j.conbuildmat.2005.09.006.

Williams, B. A., Willis, J. R. and Shacat, J. (2020). Asphalt pavement industry survey on recycled materials and warm-mix asphalt usage: 2019 (No. IS 138 (10e)). Washington: Federal Highway Administration.

Ye, Z. et al. (2009). Evaluation of effects of weather information on winter maintenance costs. Transportation research record, 2107(1), pp. 104–110. https://doi.org/10.3141/2107-11.

Zaumanis, M., Mallick, R. B. and Frank, R. (2014). Determining optimum rejuvenator dose for asphalt recycling based on Superpave performance grade specifications. Construction and Building Materials, 69, pp. 159–166. https://doi.org/10.1016/j.conbuildmat.2014.07.035.

Zhou, F. et al. (2018). Toward the development of performance-related specification for bio-rejuvenators. Construction and Building Materials, 174, pp. 443–455. https://doi.org/10.1016/j.conbuildmat.2018.04.093.

## ANNEX 1

Scenario A – Identification of the time required to restore all regional roads in an emergency state and the potential for annual repairs without the use of RAP

| Region | Annual average capital expenditure (in EUR) | Amount (EUR, without Rm) | Years* | Potential** |
|---|---|---|---|---|
| South Bohemia | 46,814,510 | 153,014,970 | 3.3 | 698 |
| Pilsen | 43,373,790 | 125,891,872 | 2.9 | 647 |
| South Moravia | 48,389,195 | 108,156,483 | 2.2 | 722 |
| Vysočina | 42,758,088 | 124,831,997 | 2.9 | 637 |
| Carlsbad | 21,459,804 | 51,342,761 | 2.4 | 320 |
| Ústecký | 29,400,774 | 104,217,657 | 3.5 | 438 |
| Královéhradecký | 26,201,070 | 93,786,890 | 3.6 | 391 |
| Liberecký | 26,221,756 | 60,703,504 | 2.3 | 391 |
| Pardubický | 21,178,232 | 89,942,792 | 4.2 | 316 |
| Olomoucký | 34,694,528 | 88,537,512 | 2.6 | 517 |
| Zlínský | 29,200,883 | 53,247,342 | 1.8 | 435 |
| Central Bohemia | 47,280,490 | 236,598,840 | 5.0 | 705 |
| Moravia-Silesia | 47,093,661 | 85,231,810 | 1.8 | 702 |
| **Total** | **464,066,782** | **1,375,504,430** | **3.0** | **6,919** |

** Note 1: "Years" means the number of years needed to reconstruct all roads in an emergency state.*

*** Note 2: "Potential" means the maximum potential length in km for road reconstruction in one financial year.*

## ANNEX 2

Scenario B – Identification of the time needed to restore all regional roads in an emergency state and the potential for annual repairs using RAP

| Region | EUR with Rm | Possible savings (in EUR) | Years* | Potential** |
|---|---|---|---|---|
| South Bohemia | 114,267,242 | 38,747,728 | 2.4 | 935 |
| Pilsen | 94,012,481 | 31,879,391 | 2.2 | 866 |
| South Moravia | 80,768,195 | 27,388,287 | 1.7 | 967 |
| Vysočina | 93,220,997 | 31,611,000 | 2.2 | 854 |
| Carlsbad | 38,341,318 | 13,001,442 | 1.8 | 428 |
| Ústecký | 77,826,792 | 26,390,865 | 2.6 | 587 |
| Královéhradecký | 70,037,391 | 23,749,499 | 2.7 | 523 |
| Liberecký | 45,331,656 | 15,371,848 | 1.7 | 524 |
| Pardubický | 67,166,728 | 22,776,065 | 3.2 | 423 |
| Olomoucký | 66,117,304 | 22,420,208 | 1.9 | 693 |
| Zlínský | 39,763,606 | 13,483,737 | 1.4 | 583 |
| Central Bohemia | 176,685,307 | 59,913,533 | 3.7 | 944 |
| Moravia-Silesia | 63,648,699 | 21,583,110 | 1.4 | 941 |
| **Total** | **1,027,187,717** | **348,316,712** | **2.2** | **9,268** |

* Note 1: "Years" means the number of years needed to reconstruct all roads in an emergency state.

** Note 2: "Potential" means the maximum potential length in km for road reconstruction in one financial year.