Effect of Overloaded Vehicles on Whole Life Cycle Cost of Flexible Pavements

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Abstract. The phenomenon of vehicle overloading—illegal exceeding of maximum legal weight of vehicles, is a serious problem both in developing and developed countries around the world. Overloaded vehicles occur less frequently in comparison to properly loaded vehicles but due to their greater potential to cause damage they significantly contribute to distress of pavement structure. As studies show, the number of overloaded vehicles increases when the control of traffic is insufficient. Weigh in Motion (WIM) systems significantly improve control level and contribute to decrease in the number of overloaded vehicles. Data delivered from WIM were used to perform statistical analysis of vehicle overloading in Poland. The average percentage of overloaded vehicles (OV) in Poland varies from 5% for roads with high enforcement level to 23% for roads where control is poor. Every weighed vehicle was considered in terms of exceeding maximum legal gross weight and maximum legal axle load. For each vehicle separately truck equivalency factors were calculated. Subsequently the relationship between average values of truck equivalency factors and percentages of overloaded vehicles was found. This relationship was used as a basis to determine the impact of overloaded vehicles on decrease in fatigue life of pavement structure (DFL) and increase factor IF, which expresses the extension of service period. It was proved that reduction of overloaded vehicles from 23 to 5% will contribute to increase in service period of pavement structures by factor 1.5. The life cycle cost analysis (LCCA) was performed for two levels of overloading OV = 23% and OV = 5%. The paper revealed that improvement of vehicle control and reduction of the percentage of overloaded vehicles from 23 to 5% will cause the reduction of whole life cost borne by road authority by 11%.

1 Introduction

1.1 Background

In Poland for the last two decades the traffic of heavy vehicles on the main roads network has been increasing rapidly. Especially in the vehicle class of five-axle trucks with semi-trailer it was noted that an average increase by five times occurred (GDDKiA 2015). After accession of Poland to the European Union in 2005 the maximum legal weight increased to 115 kN per single drive axle as a consequence of the European Union Council Directive 96/53/EC. It resulted in an increase in real axle loads of vehicles. Moreover,

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a significant fraction of vehicles exceed the legal limits of gross weight and axle loads (Szydlo and Wardega 2003; Zofka et al. 2014; Rys et al. 2016a, b).

The simplest statistical value used to describe the problem of vehicle overloading is the percentage of overloaded vehicles in the total number of trucks. It is observed that the percentage of overloaded vehicles is much higher in developing countries and can reach an extremely high level of 80% according to studies of Zhao et al. (2012) and Mulyono and Antameng (2010). In developed countries it is in lower range from 10 to 30% (Mohammadi and Shah 1992; Pais et al. 2013; Fiorillo and Ghosn 2014).

Overloaded vehicles have much greater potential to cause pavement distress in comparison to properly loaded vehicles (Jeongho Oh et al. 2007; Wang and Zhao 2016). The damaging effect of overloaded vehicles depends not only on their percentage in total number of trucks, but also on the probability distribution of vehicle loads (Mohammadi and Shah 1992; Rys et al. 2016a, b). The truck-induced damage cost varied significantly between thin and thick asphalt pavements (Wang and Zhao 2016). Wang and Zhao showed that a 1% increase in overweight trucks could cause a 1.8% reduction of pavement life. According to Al-Qadi et al. (2017) truck overloading causes greater pavement damage on secondary roads with low truck traffic volume.

The phenomena of vehicle overloading contribute to reduction in service period of pavements and bridges as well as an increase in the cost associated with maintaining, upgrading and replacing the highway infrastructure. According to Pais et al. (2013) the maintenance cost of road calculated per one vehicle is higher by 100% for overloaded vehicles compared to the cost of the same vehicle with legal loads. The infrastructure damage costs should be recovered by proper fee for overloaded vehicles (Dey et al. 2015; Al-Qadi et al. 2017). The estimated pavement damage cost varies significantly depending on truck traffic volume and highway type. However, the level of damage cost recovery fee depends on the effectiveness of detection of overloaded vehicles and it can be improved by regular vehicle control. Moreover, regular control reduces the percentage of overloaded vehicles. According to studies carried out by Tailor et al. (2000) in the state of New York (USA), the percentage of overloaded vehicles was reduced from 30 to 2% when enforcement level was increased.

The weigh in motion (WIM) system allows to improve vehicle control and contribute to decrease in the number of overloaded vehicles. However, in Europe WIM systems are used for vehicle preselection and those recognized as potentially overloaded have to be weighed again on legalized static scales. Thus the effectiveness of WIM systems depends significantly on proper localization of the WIM station in road network (Oskarbski and Kaszubowski 2016; Budzynski et al. 2017). The recent works (Burnos and Rys 2017; Burnos and Gajda 2016; Doupal and Calderara 2008) aim to improve WIM accuracy and solve related legislation problems in order to enable usage of WIM systems for automatic identification of overloaded vehicles and imposing of fines, which would significantly contribute to efficiency of control.

1.2 Objectives

The analyses presented in this paper use data from WIM in order to (1) determine the extent to which the reduction in number of overloaded vehicles contributes to extension of service period of flexible pavements and further (2) to develop a methodology of calculation of the profits from reduction of overloaded vehicles in whole Life Cycle Cost Analysis (LCCA).

2 Determination of the Impact of Overloaded Vehicles on Service Period of Flexible Pavements

2.1 Weigh in Motion Data Used in Analysis

The analysis were a part of wider research program concerning actualization of the polish catalogue of typical flexible and semi-ridig pavement structures (Judycki et al. 2017; Rys et al. 2016a, b; Pszczoła et al. 2016). Data from 11 WIM stations on Polish national roads and motorways were used to perform analysis. The WIM stations are equipped with bending plate sensors PAT DAW 100® (A2 and DK11) or with piezo-electric quartz sensors Kistler Lineas®. Automatic vehicle classification systems are also installed in all of the stations. The WIM stations can be classified as class B7 according to COST 323 WIM classification. The information about WIM data and measurement period are given in Table 1. The data considered in this study were collected from 2010 till 2016 but the period of measuring can differ for particular WIM stations (see Table 1). In all cases periods of data collection cover whole years. The WIM stations are installed for each traffic direction separately but for further analysis data from two directions from the same road section were analyzed together as for one measuring point.

Table 1. Time of WIM measurement and number of vehicles records used in analysis

WIM station	Years of measurements	Total number of records	
		Raw WIM records of all vehicles types	Records of trucks (after filtering process)
A2	2011–2012	8,411,233	2,580,957
S7	2012	3,661,002	417,185
DK4	2010–2015	23,519,182	3,299,388
DK7	2012–2015	18,264,592	1,927,799
DK11	2010–2011	2,968,179	606,668
DK22	2013	3,969,641	638,915
DK46	2011–2016	13,323,213	2,305,126
DK75	2012–2015	17,850,479	1,951,386
DK79	2013–2015	14,362,028	1,285,706
DK94	2013–2016	13,791,140	1,608,742
DK94c	2015–2016	7,778,335	1,271,672
Total		127,899,024	17,893,544

The raw WIM data were verified using a series of filters based on vehicle parameters (e.g. axle loads, total length, axle configurations etc.). The filters were set in accordance with the WIM Data Analyst's Manual (FHWA 2010) and NCHRP Report

538 (NCHRP 2005) as well as vehicle technical parameters review. The filtering process was focused on identifying and removing invalid records from the database. In total more than 127 million passes across all types of vehicles were recorded, including cars, vans etc., out of that almost 18 million records of trucks were used in the analysis.

2.2 Problem of Overloaded Vehicles in Poland

The basis for classification of a vehicle as overloaded was the European Union Council Directive 96/53/EC which specifies the legal limits of vehicles gross weights and axle loads. The value of legal limit of vehicle gross weight depends on the class of the vehicle, e.g. for 2-axles single truck unit it is equal to 18,000 kg and for 5-axles truck with semi-trailer it is equal to 40,000 kg. The legal limit of axle loads depends on the type of the axle (steering, drive etc.), the distance to neighboring axles (single, tandem, tridem) and the suspension type. For example, in EU for single drive axles the maximum axle load equals 115 kN and for other types of single axles it is equal to 100 kN.

In the analysis, each vehicle was checked and marked if overloaded with algorithms developed specifically for this study at the Gdansk University of Technology. A vehicle was treated as overloaded according to EU Council Directive 96/53/EC in the following cases:

- The vehicle gross weight was greater than the legal limit;
- The load of a single or tandem or tridem axle was greater than legal limit;
- Both the gross weight and the axle load were greater than legal limits.

The percentage of overloaded vehicles (abbreviated further as OV) was calculated for each station and each year of measurement. The annual average percentage of overloaded vehicles and the range of its variation is presented in Fig. 1.

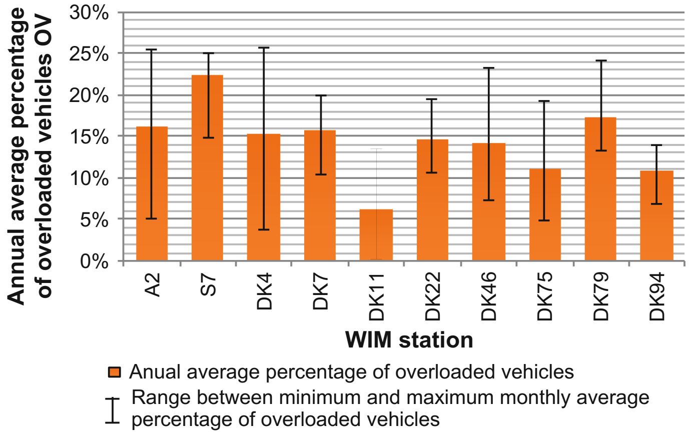

Fig. 1. Annual average percentage of overloaded vehicles OV in selected WIM stations in Poland

As it can be seen in Fig. 1 the annual average percentage of overloaded vehicles ranges from 3 to 23% depending on station and year. The maximum variations for one station do not exceed 7% over individual years. A more detailed analysis showed that the percentage of overloaded vehicles varies between days, weeks and months and was described in Rys et al. (2017). The level of enforcement can impact on this statistic. The interview with officials of the polish Road Transport Inspectorate was carried out and it provided the information, that. control on DK11 is carried out almost every day, while on S7 control is hardly ever performed. More detailed data about the frequency of controls was not available due to the confidentiality of such information. For stations where measurements were performed for several following years, like DK46, it was observed that the percentage of overloaded vehicles in first years after WIM system installation gradually decreased, which implies that installation of WIM station has a preventive effect. However, if control on legalized scales is too rare, the phenomenon of vehicle overloading intensifies, which is visible from data presented in Fig. 2 for an example station DK46. Similar changes in percentage of overloaded vehicles were observed in stations DK7, DK75 and DK94.

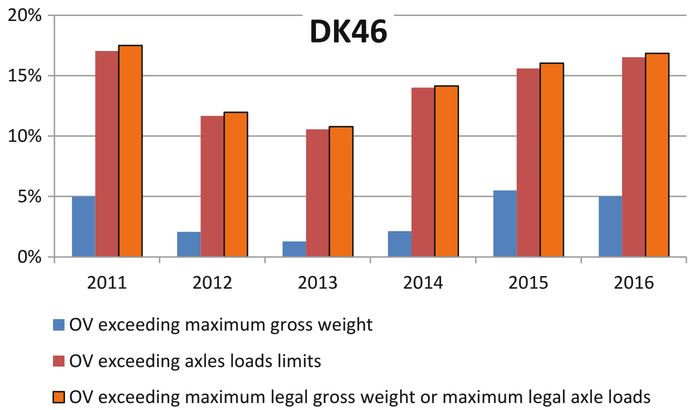

Fig. 2. Structure of vehicles overloading in successive years from 2011 to 2016 for an example station DK46

Figure 2 also includes information about character of vehicle overloading. For example in year 2015 more than 15% of vehicles exceed maximum axle load limits while 5% of vehicles exceed maximum gross weight. Similar disproportion was observed for all stations. It indicates that very often freight inside vehicles is not properly distributed, which can result from negligence and unawareness of drivers and transport companies. This observation suggests that—beside vehicle control—education of road users will contribute to decrease in the percentage of overloaded vehicles as well. To summarize the above discussion, it seems reasonable that increase in enforcement level and increase in awareness of road users can result in decrease in the percentage of overloaded vehicles to the level of 5%.

2.3 Effect of Overloaded Vehicles on Load Equivalency Factors and Truck Equivalency Factors

Truck Equivalency Factor (TF) characterizes the damaging effect of a given truck on pavement structures. The detailed procedure of calculating TF for this analysis is given in Rys et al. (2017). The fourth power equation was used to calculate load equivalency factors for particular axles in each vehicle separately and subsequently for every vehicle. As it was proved in work of Judycki (2010), fourth power equation provides similar load equivalency factors for flexible pavements as load equivalency factors determined on the basis of fatigue criteria. Damaging effects of single, dual and triple axles were considered separately according to Judycki (2006). Truck equivalency factors TF were calculated for every properly weighted vehicle and each of those vehicles was verified in terms of overloading. This approach allowed to calculate average values for different periods of time. The average truck equivalency factors TF and average percentage of overloaded vehicles OV were calculated for particular WIM stations, taking into account the whole period of analysis. The relationship between OV and TF is given in Fig. 3. More detailed analyses and relationships obtained for particular stations in monthly periods are given in Rys et al. (2017).

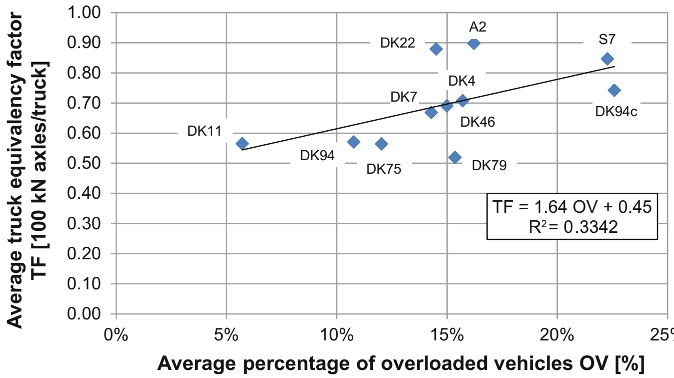

Fig. 3. Relationship between average truck equivalency factors TF and average percentage of overloaded vehicles OV obtained for particular WIM stations

It is clearly visible in Fig. 3 that an increase in percentage of overloaded vehicles OV causes an increase in truck equivalency factors TF. According to the linear regression given in Fig. 3, an increase in OV from 5 to 23% causes increase in TF from 0.53 to 0.83. The linear relationship does not seem to be very strong and coefficient of determination $R^2 = 0.33$. It is caused by three stations: DK22, A2 and DK79 whose results differ most from the general trend. The relationships between OV and TF analyzed over successive months for individual stations (Rys et al. 2017) yield much stronger correlations (with the coefficient of determination R^2 between 0.76 and 0.99), which indicates that besides overloading of vehicles some local conditions of heavy traffic have effect on truck equivalency factors as well. The model developed by Rys et al. (2016a, b) proved that axle load distribution has an impact on load equivalency factors as well and the model proposed in that publication includes axle load distributions and percentage of overloaded vehicles.

2.4 Decrease in Fatigue Life of Pavement Structures Caused by Overloaded Vehicles

The methodology of determining Decrease in Fatigue Life (DFL) of a pavement structure due to overloaded vehicles was first introduced by Rys et al. (2016a, b, 2017). The factor DFL allows to estimate how increase in percentage of overloaded vehicles contributes to decrease in fatigue life and further decrease in service period of pavement structure. The formula (1) was used to calculate decrease in fatigue life of pavement structures:

$$\mathrm{DFL} = 1 - \frac{\mathrm{TF}_0}{\mathrm{TF}_{\mathrm{OV}}} \tag{1}$$

where: DFL—Decrease in Fatigue Life caused by overloaded vehicles, TF_0—Truck equivalency factor at 0% of overloaded vehicles, $\mathrm{TF}_{\mathrm{OV}}$—Truck equivalency factors at a given percent of overloaded vehicles OV. The relationship between DFL and percentage of overloaded vehicles OV is shown in Fig. 4 and it is compared with factors DFL obtained from two previous works by the authors (Rys et al. 2016a, b, 2017).

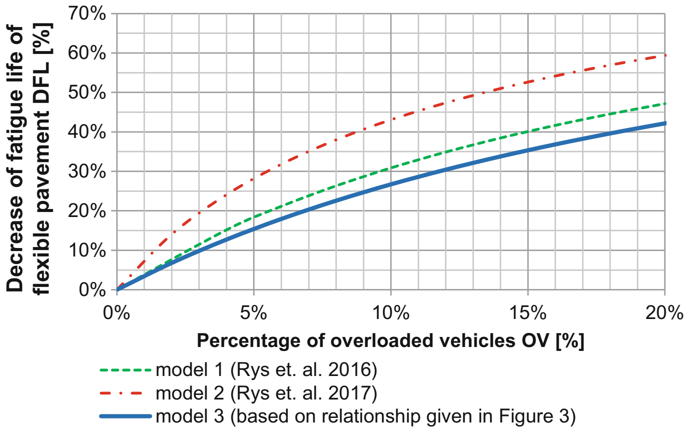

Fig. 4. Relationship between Decrease in Fatigue Life DFL and average percentage of Overloaded Vehicles OV obtained for three different statistical models

It can be concluded from Fig. 4 that three different approaches to determination of impact of percentage of overloaded vehicles on load equivalency factors LEF or truck equivalency factors TF yield similar results of parameter DFL. An increase in percentage of overloaded vehicles from 0 to 20% results in a decrease in fatigue life by 40 up to 60%. For further analysis the model 3 given in Fig. 4 was used to calculate increase in service period due to reduction of the number of overloaded vehicles.

2.5 Extension of Residual Fatigue Life and Service Period of Flexible Pavement Structures Due to Reduction of Number of Overloaded Vehicles

On the basis of Eq. (1) and Fig. 4 the following simple approach is proposed to estimate the effect of reduction in percentage of overloaded vehicles on the extension of residual fatigue life and service period of flexible pavement structure (Rys et al. 2017). The fatigue life depends on the truck equivalency factor TF and total number of trucks NT in the entire service period. Better traffic control may cause reduction in percentage of overloaded vehicles OV thus reducing the value of the truck equivalency factor TF. If the truck equivalency factor TF decreases as a consequence of decrease in the percentage of overloaded vehicles OV, the total number of trucks NT which the pavement can carry before failure will increase and consequently, the residual fatigue life and service period will be extended. To evaluate the extension of residual fatigue life and service period of flexible pavement structures due to decrease in number of overloaded vehicles let us assume that the residual fatigue life of a given pavement was assessed based on measurement obtained from the FWD test. The percentage of overloaded vehicles OV for that road is known. To calculate the residual fatigue life and service period of the pavement in case when number of overloaded vehicles is reduced by ΔOV the following formula can be used:

$$RFL_{OV-\Delta OV} = RFL_{OV}\frac{1 - DFL_{OV-\Delta OV}}{1 - DFL_{OV}} \tag{2}$$

where: $\mathrm{RFL}_{\mathrm{OV}-\Delta\mathrm{OV}}$—Residual Fatigue Life, expressed as number of Equivalent Single Axle Loads, after reduction of overloaded vehicles percentage from OV to (OV − OV), $\mathrm{RFL}_{\mathrm{OV}}$—Residual Fatigue Life, expressed as number of Equivalent Single Axle Loads, at the existing number of overloaded vehicles OV, $\mathrm{DFL}_{\mathrm{OV}-\Delta\mathrm{OV}}$—Decrease in Fatigue Life at reduced percentage of overloaded vehicles (OV − ΔOV), $\mathrm{DFL}_{\mathrm{OV}}$—Decrease in Fatigue Life at existing percentage of overloaded vehicles OV. The DFL value (Decrease in Fatigue Life) is given in Fig. 4, as a function of percentage of overloaded vehicles OV.

Similarly the extended residual service period of a pavement after reduction of number of overloaded vehicles by ΔOV can be calculated from the formula:

$$RSP_{OV-\Delta OV} = RSP_{OV}\frac{1 - DFL_{OV-\Delta OV}}{1 - DFL_{OV}} \tag{3}$$

where: $\mathrm{RSP}_{\mathrm{OV}-\Delta\mathrm{OV}}$—Residual Service Period, expressed in years, after reduction of overloaded vehicles percentage from OV to (OV − ΔOV), $\mathrm{RSP}_{\mathrm{OV}}$—Residual Service Period, expressed in years, at the existing number of overloaded vehicles OV. Both values—Residual Fatigue Life as well as Residual Service Period—will increase by the Increase Factor IF which expresses extension of service period and is equal to:

$$IF = \frac{1 - DFL_{OV-\Delta OV}}{1 - DFL_{OV}} \tag{4}$$

where IF is the Increase Factor, other abbreviations as above. The chart with IF for three target percentages of overloaded vehicles is presented in Fig. 5.

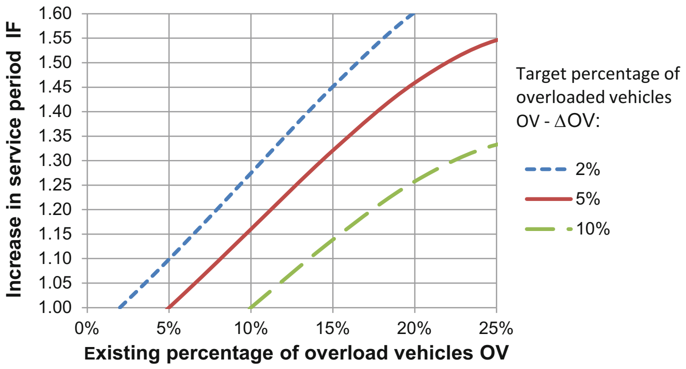

Fig. 5. Increase in service period IF due to reduction of existing percentage of overloaded vehicles to the level of 2, 5 or 10%

The presented method is approximate but may well suit a purpose of evaluating the benefits of traffic control measures. The exact value of increase in fatigue life and service period due to decrease in percentage of overloaded vehicles is dependent on several factors which may vary between specific roads. These factors are: composition and characterization of heavy traffic, current percentage of overloaded vehicles, the degree of overloading, pavement structure and materials used for pavement layers, climatic conditions, etc.

3 Example of Life Cycle Cost Analysis of Pavement with Existing and Reduced Percentage of Overloaded Vehicles

The calculations were performed for an example of national road DK94c with existing percentage of overloaded vehicles equal to 23%, Annual Average Daily Truck Traffic AADT = 1125 trucks per day per lane and truck equivalency factor TF = 0.75 standard 100 kN axles per lane. The typical design period for national roads in Poland equals 20 years. Two alternative scenarios of pavement structure loading were considered:

A. Pavement structure is loaded by heavy traffic with current 23% of overloaded vehicles and service period is equal to design period,
B. The percentage of overloaded vehicles is decreased to 5% and the service period is extended by factor IF = 1.5 (according to Fig. 5).

The same fatigue life of pavement structure was assumed for both alternatives A and B. A plot of pavement condition changes in the following years of service for alternative A and B is presented in Fig. 6. Decrease in OV from 23 to 5% will cause an increase in service period of new structure from designed 20 years to 30 years. Similarly the period between pavement structural rehabilitation will increase from designed 10 years to 15 years.

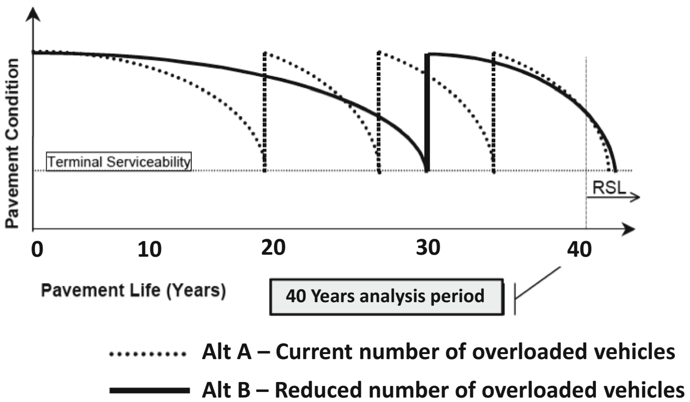

Fig. 6. Effect of reduction of overloaded vehicles on pavement condition and pavement service period

The whole life cost analysis was performed on the basis of instructions (FHWA 1998). The same initial costs and maintenance cost were assumed in both alternatives A and B. The treatment scenario can significantly vary in different countries and it depends on several factors including policy, traffic and climatic conditions, road authority experience etc. The analysis uses an example treatment scenario, which is given in Table 2. The treatment scenario was assumed on the basis of literature review available in work of Lisowska and Ludzik (2016), where a comparison of experience from several countries including USA, Canada, France and Switzerland is given.

It was assumed that costs include discount rate, which equals 2.5% and is constant over the whole period of analysis. More detailed information about maintenance strategy and costs for both alternatives A and B are given in Table 2. The costs given in Table 2 were assumed on the basis of interview with three road construction companies and Polish road authority. In order to make the analysis clearer, only costs bare by road authority were included. The presented analysis does not include user costs but it is expected that consideration of user costs would additionally increase the disproportion between alternatives A and B.

It can be concluded from Table 2 that for the assumed treatment scenario the whole life costs borne by road authority can decrease by 11% if the percentage of overloaded vehicles decreases from 23 to 5%. The results could be slightly different for other treatment scenarios, however the extension of service period will always result in cost

Table 2. Example of maintenance treatment and calculation of costs bare by road authority in case of existing and reduced percentage of overloaded vehicles

Year of analysis	Alternative A Existing percentage of overloaded vehicles OV = 23%		Alternative B Percentage of overloaded vehicles reduced to OV = 5%	
	Maintenance treatment	Cost bare by road authority (per one km)	Maintenance treatment	Cost bare by road authority (per one km)
0	**Initial cost—construction of new pavement**	**$1,342,857**	**Initial cost—construction of new pavement**	**$1,342,857**
5	Crack sealing (~200 m)	$1768	Crack sealing (~200 m)	$1768
10	Crack repairs Thin overlay	$34,523	Crack sealing Repairs of potholes with patches 2% of lane area	$3348
15	Crack sealing Repairs of potholes with patches 2% of lane area	$3348	Crack repairs, milling and reconstruction of wearing course	$47,346
20	Milling of wearing course, overlay with 12 cm of HMA	$217,954	Crack sealing Repairs of potholes with patches 5% of lane area	$6975
25	Crack repairs	$2312	Crack sealing Repairs of potholes with patches 5% of lane area	$6164
30	Crack sealing Repairs of potholes with patches 5% of lane area	$5448	Milling of wearing course, overlay with 8 cm of HMA	$170,265
35	Full-depth reconstruction	$216,705	Crack sealing and repairs	$1806
40	Crack sealing	$745	Crack sealing Repairs of potholes with patches 5% of lane area	$4256
	Salvage value	**−$102,567**		**−$56,782**
	Total cost	$1,723,093		$1,528,004

benefits. The value of 11% does not seem to be very high, however considering maintenance costs of the entire road network it brings multi-million savings.

4 Conclusions

(1) Data from Weigh in Motion stations on seven state roads and one motorway in Poland indicated that the percentage of overloaded vehicles was in the range from 5 to 23%. The lowest percentage was noted on a road where continuous control of traffic was performed.
(2) Most overloaded vehicles exceeded the maximum legal axle load limit, while the gross weight was exceeded less frequently. It indicates that very often freight inside vehicles is not properly distributed which may result from negligence and unawareness of drivers and transport companies.
(3) The relationship between average percentage of overloaded vehicles and average truck equivalency factor was found in the research. According to the linear regression, an increase in percentage of overloaded vehicles from 5 to 23% causes increase in truck equivalency factor from 0.53 to 0.81—by 1.52 times. Increase in truck equivalency factor results in decrease in fatigue life of pavement structure.
(4) Reduction of number of overloaded vehicles causes extension of residual fatigue life and service period of pavement structures. The methodology of estimation of Increase Factor IF which expresses extension of service period was developed in the paper. Reduction of percentage of overloaded vehicles from 23 to 5% causes increase in service period by IF = 1.5.
(5) The example analysis of effect of overloaded vehicles on life cycle cost of pavement structure was performed. For a given example the whole life cycle costs bare by road authority can decrease by 11% when percentage of overloaded vehicles decreases from 23 to 5%. The results may be slightly different for other treatment scenarios, however the extension of service period will always result in cost benefits. Reduction in number of overloaded vehicles can brings multi-million savings when maintenance costs of the entire road network are considered.

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