Maintenance interval optimization based on fuel consumption data via GPS monitoring

Z. Aleš, J. Pavlů* and V. Jurča

Faculty of Engineering, CULS-Czech University of Life Sciences Prague, Kamycka 129, 16521 Prague 6, Czech Republic;
*Correspondence: jindrichpavlu@seznam.cz

Abstract. Properly performed preventive maintenance is one of the basic conditions for ensuring the operability of the mobile machines. There are basically two types of preventive maintenance: scheduled maintenance with pre-determined intervals and maintenance by the technical state. Common practice shows that maintenance intervals are often determined only by a qualified estimate of the machine manufacturer or maintenance manager, which results in costs increase. The authors proposed new method of using the modern technology of Global Positioning System, in order to reduce costs of preventive maintenance. Mentioned technologies allow users to monitor a number of operational parameters of mobile machinery in real time. Collected data obtained from the operation can be used for decision-making of maintenance activities. For ensuring the availability of mobile machinery it is important to determine the optimal maintenance interval. The authors proposed method for using data from satellite monitoring using the criterial function in order to determine the optimal interval for performing preventive maintenance. Proposed method is demonstrated on the example of accurate determination of preventive maintenance intervals for several mobile machines. Using data from satellite monitoring and subsequent data processing contribute to better maintenance planning and consequently to economical operation.

Key words: maintenance interval, preventive maintenance, maintenance costs, satellite monitoring.

INTRODUCTION

There are two basic maintenance systems for ensuring preventive maintenance (CSN EN 13306, 2002) of vehicles and mobile machines - maintenance by the technical state (condition-based maintenance – on-board diagnostic) (Honig et.al., 2014) or maintenance according predetermined operating time intervals (general unit w; examples: travelled distance (km), operated hours (hrs) measured by hour meter, etc.) (Drozyner & Mikolajczak, 2007). Amount of the specific fuel consumption is possible indicator used as an overall diagnostic signal in the maintenance system according to technical state of mobile machines (Lan & Kuo, 2003; Jin et al., 2009). Monitoring of specific fuel consumption faces several problems – a relatively accurate measurement of the roller bed test is very expensive, and furthermore, there are problems with the measurement of combustion engines with high power and engines of some construction machinery. Significantly cheaper acceleration methods are not without problems too, especially when measuring the nowadays conventional turbocharged engines, where delay of turbocharger during engine acceleration must be eliminated by various correction methods. For these reasons, second system (i.e. maintenance according predetermined operating time intervals) is mostly applied for group of construction machinery and machines with high power engines (Pexa & Marik, 2014).

Maintenance intervals are often determined only by a qualified estimate of the machine manufacturer or maintenance manager, which results in costs increase of operating machines – if the intervals are too short, it leads to unnecessary increase in maintenance costs, on the other hand, if the intervals are too long it also leads to increase of costs resulting from the poor technical condition of machines (Wiest, 1998). In addition, predetermined intervals do not precisely reflect operational utilization of a particular machine; the interval is set for the entire group of machines of the same type. Attempts to use known methods of mathematical optimization of preventive maintenance is problematic (Kucera et al., 2013). Known stochastic models are based on knowledge of the probability of failure in different periods of durability of technical object. This way of determination of optimal preventive maintenance interval requires usage of statistical methods and monitoring of a number of other machine operational indicators (dependability characteristics). The required stochastic model of renewal could be described and formulated after analysis of the history of machine operation (Eti et al., 2006; Jardine & Tsang, 2006; Jurca & Ales, 2007).

One of the other options how to determine the optimal preventive maintenance interval is the application of renewal theory using data from satellite monitoring equipment (Darnopykh, 2010). Satellite monitoring of mobile machinery is now relatively common, but companies use it in a very limited way – practically only for monitoring of machines (operational state, position, etc.). Transmitted data recorded via satellite monitoring can be utilized in more sophisticated way. In order to achieve such a goal, authors propose to set up and apply proper algorithm for data processing. Based on data of fuel consumption it is possible to determine the optimal preventive maintenance interval of a particular machine and determine the losses which result from not complying with optimal maintenance interval.

Algorithm of determination of optimal preventive maintenance interval is based on the known value of preventive maintenance costs and slope of linear trend of specific fuel consumption, which is obtained by processing data from a satellite monitoring of machinery. Calculated optimal preventive maintenance interval is corrected according to increasing operating time. In addition, it is possible to verify if previous maintenance interval was chosen correctly and how effectively operator of machinery contributes to production efficiency and effect of change in operating conditions, etc (Jurca et al., 2008).

MATERIALS AND METHODS

Principle of operational monitoring using GPS (Global Positioning System) of machinery is widely known (Geske, 2007; Cai et al., 2011; Grieshop et al., 2012), therefore there are only briefly described issues related to this paper. After turning on the ignition system of vehicle, control unit starts up from sleep mode and starts to track and store data into its memory and connects to the server (Kans, 2008). After connecting the control unit quickly sends the recorded data and subsequently data sends at specified intervals, for instance in 120 second intervals. Data is processed in the device according to the configuration file. Obtained data is in a various form: immediate values, maximum or minimum for the recorded period, the average, statistical parameters and it is also possible to apply various filters, and all data is conveniently available from user web application.

In order to use the theory of renewal to determine the optimal maintenance interval of machinery it is important to measure fuel consumption with sufficient precision. Use of the CAN-BUS information is not suitable because the accuracy is determined by the fuel float up to 10% according to CAN-BUS standard. For this reason, capacitance probe CAP04 (Partner mb.) were mounted into fuel tank.

Capacitive probe CAP04 consists of two tubes of different diameter, which are the electrodes of capacitor. The dielectric is composed of electrically non-conductive material, specifically with a fuel and air. The relative permittivity of air is $\varepsilon r = 1$, during re-fuelling the air is replaced with diesel which has relative permittivity $\varepsilon r = 2$ and due to this fact the capacity of the capacitor increases. The capacitive sensor measures the position of the boundary between air and diesel fuel.

The probe is also equipped with thermometers to sense temperature of fuel and the surface temperature of the fuel tank. The processor evaluates data according to the actual capacity of the probe to match the measured volume of diesel at a reference temperature 15 °C. This method ensures that the reported amounts of fuel are not distorted by thermal expansion of diesel. Furthermore, the probe measures the tilt of the tank in two axes. While driving terrain when the level of diesel fluctuates rapidly and strongly, the probe indicates stable signal by means of appropriate filters of the signal.

General criterial function of renewal (replacement) seeks the minimum of mean unit costs of renewal and operation – the minimum of the function marks the optimum time for renewal (see Equation 1). It is obvious, that the costs of maintenance itself act in the way of prolonging the standard preventive maintenance period. Conversely, the costs of operation, which rise due to worsening technical condition when extending the maintenance period, make the preventive maintenance period as short as possible. The sum curve $u(\bar{t})$ must have a local minimum, which needs to be found in order to determine the optimum period of preventive maintenance. Specific fuel consumption is a comprehensive diagnostic signal indicating instantaneous extent of wear of machine. (Legat et al. 1996)

$$u(\bar{t}) = \frac{N_O + N_P(\bar{t})}{\bar{t}} \rightarrow \min \qquad (1)$$

where: NO – Costs of renewal (CZK); $N_P(\bar{t})$ – Costs of operation (CZK); $\bar{t}$ – mean time of operation (w); $u(\bar{t})$ – mean unit costs of renewal and operation (CZK w^{-1}).

Author's proposed method for optimizing maintenance intervals of machinery uses information about fuel consumption that is assessed for each day of machine's operation in unit l,100 km^{-1} or l hrs^{-1}.

For the calculation of the local minimum of a function of mean unit costs, its first derivative set equal to 0, thus:

$$\frac{\partial u(\bar{t})}{\partial \bar{t}} = \frac{\frac{\partial N_P(\bar{t})}{\partial \bar{t}} \cdot \bar{t} - \left[N_O + N_P(\bar{t})\right]}{\bar{t}^2} \tag{2}$$

$$\frac{\partial N_P(\overline{t_O})}{\partial \overline{t_O}} \cdot \bar{t}_O - \left[N_O + N_P(\overline{t_O})\right] = 0 \tag{3}$$

$$\frac{\partial N_P(\overline{t_O})}{\partial \overline{t_O}} = \frac{N_O + N_P(\overline{t_O})}{\overline{t_O}} \tag{4}$$

The right side of equation (4) equals to the intermediate mean unit costs $u(\bar{t}_O)$ at optimum of operating time for renewal. The left side of the equation (4) equals to the intermediate immediate operation unit costs $v_P(\bar{t}_O)$ at optimum of operating time for renewal. The equation describes that the optimal moment of renewal, i.e. a local minimum of the criterial function when immediate operation unit costs equal to the mean unit costs of operation and renewal.

Consequently, in order to find the minimum of sum function $u(\bar{t})$ it is necessary to know two basic values – renewal costs N_O (the costs of performed maintenance) and mean unit costs of operation $u_P(\bar{t})$, which are based on the tracking of specific fuel consumption (therefore, it is necessary to determine the equation of growth trend of specific fuel consumption).

RESULTS AND DISCUSSION

Proposed algorithm for determining the optimum of maintenance interval is using MS Excel spreadsheet. Imported data on specific fuel consumption of the machine are listed in the table by date and time of their recording and from these data it is necessary to select only the data which characterize the utilization of machinery. The algorithms for data filtering are different according to different groups of machines and their utilization. For example, when filtering data on fuel consumption of truck the algorithm filters out data on fuel consumption at idle mode of engine – the engine consumes fuel, but the distance travelled is zero – the value of specific fuel consumption (litres 100 km^{-1}) is reaching the infinity. Specific fuel consumption of construction equipment is evaluated in litres per operating hours – changing position of the machine cannot be used for filtering data, on the contrary for some machines (e.g. excavators) change of position has to be excluded from data processing because machinery does not perform intended work. A properly designed algorithm for filtering data affects the entire primary data processing and results of optimal maintenance interval of a particular machine.

After selection, the mean specific fuel consumption is calculated for each day and linear trend is constructed.

Specific fuel consumption is a comprehensive diagnostic signal and depends on many operational factors and therefore there is large variance in monitored specific fuel consumptions.

The unit costs of operation $u_P(\bar{t})$ are determined by a linear trend, which is set by slope of specific fuel consumption trend and the average price of diesel fuel (1.2 EUR l^{-1} – November 2014) during vehicle operation. Slope of specific fuel consumption trend is calculated from the cumulative fuel consumption (polynomial function of second degree, Fig. 1) divided by operational time.

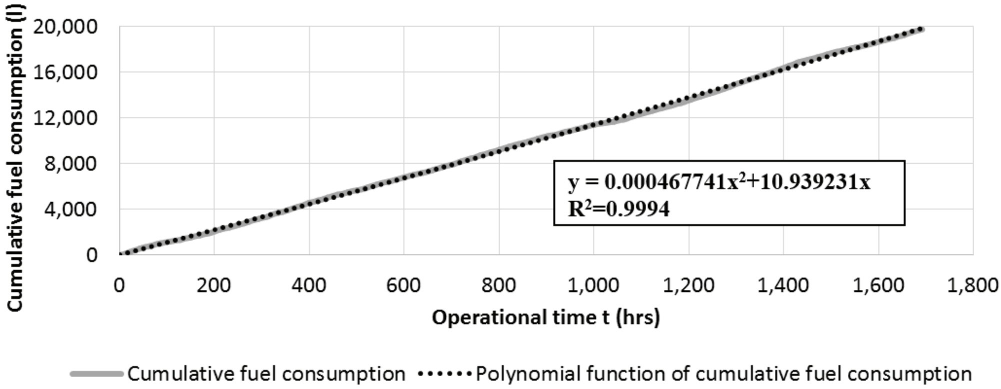

Figure 1. Cumulative fuel consumption with polynomial function of second degree.

The function of the mean unit costs is determined by the sum of two functions – unit operational costs function and unit costs of replacement function. The optimal maintenance interval is determined by a local minimum of the mean unit costs function. In this case, the function $u_P(\bar{t})$ is linear, the local minimum of the function $u(\bar{t})$ located at the same spot as intersection of both forming curves $u_O(\bar{t})$ and $u_P(\bar{t})$. The specific examples of the graphic solution are shown in Fig. 2.

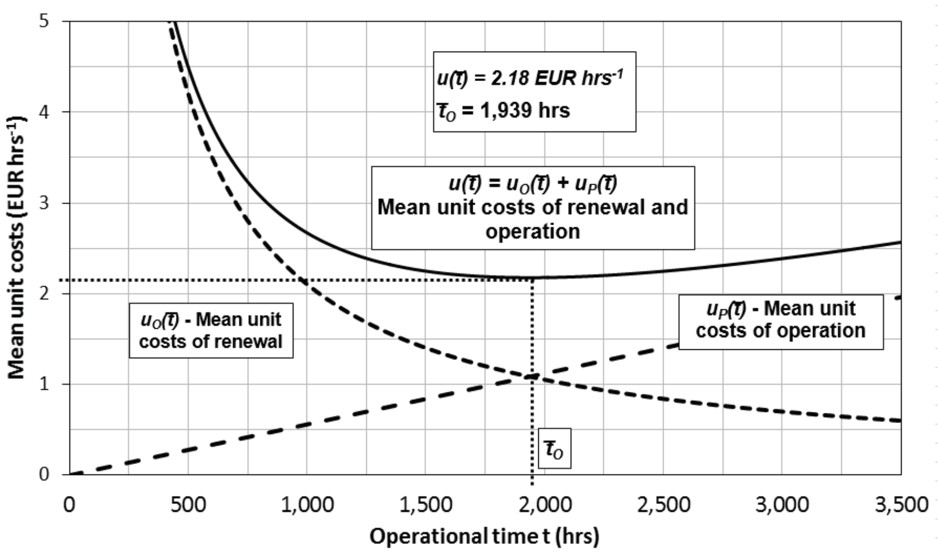

Figure 2. Determination of maintenance intervals of TATRA 815 – graphic interpretation.

Proposed method is applied for truck TATRA 815 operated in construction site. The costs of renewal (maintenance) for this truck are estimated at 2,110.14 EUR. In this particular case, the amount of 2,110.14 EUR represents costs of diagnostic maintenance of motor vehicle TATRA 815. Maintenance is performed within one working day and during this day the maintenance costs are calculated as follows:

1) The driver generates a financial loss during the day when the maintenance is carried out because transport of vehicle to the service shop and back does not generates any profit, but the driver has to be paid anyway. The financial loss can be calculated as follows: 1,000 EUR month^{-1} (driver's salary) × 1.35 (deductions from wages) / 20 (working days) = 67.50 EUR.

2) The financial loss due to downtime of the vehicle is calculated: 1.25 EUR km^{-1} (the price of material transported by vehicle) × 220 km day^{-1} (the average distance travelled per day) = 275 EUR.

3) The financial loss occurred due to fuel consumed on a journey into and back: 42 l 100 km^{-1} (average specific consumption of the vehicle) × 35 km (average distance to the maintenance service and back) × 1.2 EUR l^{-1} = 17.64 EUR.

4) Costs of diagnostic maintenance = 750 EUR

5) The price of labour after diagnostic maintenance and the average price of spare parts (e.g., fuel, air and oil filter, injector, pump alignment, oil change, etc.) = 1,000 EUR.

This practical example shows that the optimal preventive maintenance interval is 1,939 hrs for vehicle TATRA 815 (Fig. 1). After rounding to the nearest hundred hours the maintenance interval is set to 2,000 hrs.

For the calculated procedure, it is clear that the maintenance interval is variable and can be influenced by:

- Maintenance costs,
- Function of mean unit operational costs (influenced by fuel costs).

Specific fuel consumption is influenced by the conditions of operation of the machine and therefore determined maintenance interval has to be continually updated. Data analysis of plenty same types of vehicles will help determine the intervals for maintenance for a particular type of machine and use it for simple long-term maintenance planning of mobile machines in the enterprise (see examples below in Table 1).

Table 1. Determination of the mean maintenance interval for TATRA 815 and Renault Kerax

Vehicle	Operational time (hrs)	Polynomial function	Trend of slope of specific fuel consumption	Determined maintenance interval t_O
01 TATRA 815	1,692	$0.00046x^2 + 10.9x$	0.0005612894	1,939 hrs
02 TATRA 815	1,856	$0.00042x^2 + 9.6x$	0.0005108268	2,032 hrs
03 TATRA 815	1,848	$0.00051x^2 + 9.8x$	0.0006150768	1,852 hrs
01 Renault Kerax	1,765	$0.00026x^2 + 9.1x$	0.000322144	2,559 hrs
02 Renault Kerax	1,986	$0.00031x^2 + 8,8x$	0.000375100	2,372 hrs
03 Renault Kerax	1,848	$0.00028x^2 + 8,9x$	0.0003414192	2,486 hrs

Table 1 provides data on vehicle type, monitored time of operation (hrs), polynomial function, slope of linear trend of specific fuel consumption and data of specified maintenance intervals τ_O (hrs). Slope of linear trend of specific fuel consumption is different for each particular vehicle. Such a fact is due to different operational conditions of certain vehicles and also due to different style of driving of drivers. For example, slope of trend for vehicles Renault Kerax range from 0.000322144 to 0.0003751. Determined optimal intervals were calculated with N_O = 2,110.14 EUR and average fuel costs 1.2 EUR per litre. Mean maintenance interval for vehicles Renault Kerax was 2,500 hrs and for TATRA 815 was 2,000 hrs.

The same algorithm can be used for any type of machinery (transportation, construction, mining, railroad, agricultural, etc.), but with the difference of operational time unit (kilometres, tones, hectares, volumes, etc.).

CONCLUSIONS

The paper presents proposed methodology for optimization of planned preventive maintenance, which is based on the use of data from satellite monitoring - data collection, their final selection and algorithmic processing and therefore finding optimal preventive maintenance interval for a particular machine or group of machines. Algorithm of determination of optimal preventive maintenance interval is based on renewal theory and its modification for solving particular problem. Principle of this algorithm is based on minimization of operational and renewal costs.

The proposed methodology for determining the optimal maintenance interval is particularly suitable for companies that already use satellite monitoring, but mostly in its elementary form for the current position of the vehicle, construction equipment downtime monitoring, etc. It is obvious that the observed specific fuel consumption relatively largely varies, which is influenced by variability of operating conditions, load weight, driver's driving style, nature of extracted material within construction machinery, etc. This variance is eliminated by large quantities of raw data and therefore processing of raw data allows for a precise determination of the optimal preventive maintenance interval for a specific machine, its current operational conditions and the changes of their technical state during deterioration.

Algorithm of data processing from satellite monitoring provides timely reports on individual machine maintenance requirements and enables continuous refinement of maintenance intervals during operational time. Suspiciously different maintenance interval of particular machine (calculated optimal maintenance interval deviates from the average) might be followed by detailed diagnostics in order to determine the causes of short maintenance interval. Proposed algorithm may contribute to better maintenance planning and consequently to economical operation of machinery.

ACKNOWLEDGEMENTS. Paper was created with the grant support – CZU 2014: 31190 / 1312 / 3128 – Utilization of satellite monitoring for detection of operational parameters of machines.

REFERENCES

Cai, S., Becherif, M., Henni, A., Wack, M, & Aboubou, A. 2011. Processing of information gathered from hybrid or electrical vehicle for reduction of fuel consumption and gas emission. *Mediterranean Journal of Measurement and Control* **7**(2), 236–242.

CSN EN 13306 (2002): Maintenance terminology. Prague: The Czech Office for Standards, Metrology and Testing. (In Czech)

Drożyner, P. & Mikołajczak, P. 2007. Maintenance of vehicles, machines and equipment in view of the ISO 9001 requirements. *Eksploatacja i Niezawodność - Maintenance and Reliability* **4**, 55–58.

Darnopykh, V.V. 2010. Application of unified methodical approach to online planning of target operation of satellite monitoring and communication systems. *Journal of Computer and Systems Sciences International* **49**(1), 115–134.

Eti, M.C., Ogaji, S.O. & Probert, S.D. 2006. Reducing the cost of preventive maintenance (PM) through adopting a proactive reliability-focused culture, *Applied Energy* **83**, 1235–1248.

Geske, D.M. 2007. Mapping a cleaner route. *Diesel Progress North American Edition* **73**(6), 108–109.

Grieshop, A.P., Boland, D., Reynolds, C.C., Gouge, B., Apte, J.S., Rogak, S.N. & Kandlikar, M. 2012. Modelling air pollutant emissions from Indian auto-rickshaws: Model development and implications for fleet emission rate estimates. *Atmospheric Environment* **50**, 148–156.

Hönig, V., Horníčková, Š. & Orsák, M. 2014. Monitoring of wear particles during running-in diesel engines of tractors. *2nd International Conference on Materials, Transportation and Environmental Engineering, CMTEE 2014.* Kunming; China, Volume 1030–1032, 1206–1209.

Jardine, A. & Tsang, A. 2006 Maintenance, replacement, and reliability: theory and applications. *Mechanical engineering, Boca Raton: CRC/Taylor*, 322. ISBN 08-493-3966-9.

Jin, G., Xiang, Z. & Lv, F. 2009 Semantic Integrated Condition Monitoring and Maintenance of Complex System. *In: IEEE 16th International Conference on Industrial Engineering and Engineering Management*. Beijing, PRC, pp. 670–674.

Jurca, V. & Ales, Z. 2007. Maintenance Management Efficiency Evaluation. *Eksploatacja i Niezawodnosc – Maintenance and Reliability* **1**, 13–19.

Jurca, V., Hladik, T. & Ales, Z. 2008. Optimization of Preventive Maintenance Intervals. *Eksploatacja i Niezawodność - Maintenance and Reliability* **3**, 41–44.

Kans, M. 2008. An approach for determining the requirements of computerised maintenance management systems. *Compunters in industry* **59**, 32–40.

Kučera, M., Aleš, Z., Ivandić, Z. & Hujo, L. 2013. Possibility of hydraulic fluids with a low environmental impact application in agriculture and transport machinery. *Journal of Central European Agriculture* **14(4)**, 1575–1584.

Lan, L. W. & Kuo, A.Y. 2003. Modelling bus drivers' aberrant behaviours and the influences on fuel and maintenance costs. *Journal of Advanced Transportation* **38 (1)**, 93–113.

Legat, V., Zaludova A.H., Cervenka, V. & Jurca, V. 1996. Contribution to optimization of preventive replacement. *Reliability Engineering and System Safety* **51**, Elsevier Science Limited, ISSN 0951-8320. 259–266.

Pexa, M. & Mařík, J. 2014. The impact of biofuels and technical engine condition to its smoke - Zetor 8641 Forterra. *Agronomy Research* **12**(2), 367–372.

Wiest, W. 1998 Improvement of the availability through quality control and preventive maintenance of self-propelled vehicles. *In: Conference on Agricultural Engineering, VDI BERICHTE* **1449**, Germany, pp. 351–356.