UTILIZATION OF SATELLITE MONITORING FOR DETERMINATION OF OPTIMAL MAINTENANCE INTERVAL*

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Properly performed preventive maintenance is one of the basic conditions for ensuring the operability of the mobile machines. Basically there are two types of preventive maintenance: scheduled maintenance with pre-determined intervals and maintenance according to 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 a new method of using the modern technology of Global Positioning System and General Packet Radio Services, in order to reduce costs of preventive maintenance. The mentioned technology allows the 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. In order to determine the optimal interval for performing preventive maintenance, the authors proposed a method of exploiting data from satellite monitoring using the criterial function. The 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.

preventive maintenance; maintenance costs; criterial function

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 (result of diagnostics – condition-based maintenance – on-board diagnostic) (Barone, 2006; Barone et al., 2007) or maintenance according to predetermined operating time intervals (general unit *w*; examples: travelled distance (km), operated hours (h) measured by hour meter, etc.) (Drożyner, Mikołajczak, 2007). Amount of the specific fuel consumption is a 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 the group of construction machinery and machines with high power engines (Westerkamp, 2006).

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 an unnecessary increase in maintenance costs, on the other hand, if the intervals are too long it also leads to the 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 apply known methods of mathematical optimization on preventive maintenance are problematic (Cavalca et al., 2008). Known stochastic models are based on the knowledge of the probability of failure in different periods of durability of a technical object. This way of determination of

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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 analyzing the history of machine operation (E t i et al., 2006; J a r d i n e, T s a n g, 2006; J u r c a, A l e s, 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 (D a r n o p y k h, 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. (J u r c a et al., 2008).

MATERIAL AND METHODS

Principle of operational monitoring using GPS/GPRS (Global Positioning System/General Packet Radio Services) of machinery is widely known (G e s k e, 2007; C a i et al., 2011; G r i e s h o p et al., 2012), therefore there are only briefly described issues related to this paper. After turning on the ignition system of a vehicle, control unit starts up from sleep mode and starts to track and store data into its memory and connects to the server (K a n s, 2008). After connecting the control unit quickly sends the recorded data and subsequently it sends data 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.

The digital data is converted to physical data (on the server); this level is called 'measured data'. User application calculates'calculated data' from stored 'measured data'. Measured and calculated data allows, according to the user's algorithms, to calculate pivot tables and 'summed data'. Pivot tables represent computed data tracked over a certain period of time according the user's requirements.

Summed data is usually categorized into three groups:

(1) **Mileage/service**. This category provides information about: date and time, fuel tank START MODE (l), fuel tank STOP MODE (l), mileage from fuel tank (l), driven distance (km), time of idle running (h), time of trip (h), specific fuel consumption *m* (l per 100 km; l per h), over-consumption of fuel, distance to repair service (km), overall distance of tachograph (km).

(2) **Re-fuelling**. This category provides information about: date and time, fuel tank START MODE (l), fuel tank STOP MODE (l), losses during break (l), losses during operation (l), probe check, re-fuelling off the record (l), re-fuelling on the record (l), overall re-fuelling (l), entry data about re-fuelling (l), differences between entered and measured data (l), relative deviation between entered and measured data (%).

(3) **Time utilization**. This category provides information about: date and time, position – start of shift, start time of shift, position – finish of shift, finish time of shift, duration of operation time/shift (h), breaks (h), utilization per day (%).

In order to use the theory of renewal to determine the optimal maintenance interval of machinery it is important to measure fuel consumption with a 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 (made by Partner mb.) was mounted into the fuel tank.

Capacitance probe CAP04 consists of two tubes of different diameter, which are the electrodes of the 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 of 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.

Before installing the fuel probes, the accuracy of measurement of the probe was tested at temperatures from –15 to +55°C. Samples of diesel from three different fuel suppliers (Shell, Slovnaft, and OMW) were used for testing. The highest deviation of measurement (0.21%) was measured on a sample from Shell at 13°C. In operation the accuracy of fuel capacity probe is slightly worse (about 0.5%), which fully meets the purposes of the measurement.

General criterial function of renewal (replacement) seeks for 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 $u(t)$ 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 machine wear (Legát et al., 1996).

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

where:
N_O = costs of renewal (CZK)
$N_P(t)$ = costs of operation (CZK)
t = mean time of operation (w)
$u(t)$ = mean unit costs of renewal and operation (CZK per w)

The method for optimizing maintenance intervals of machinery proposed by the authors exploits information about fuel consumption that is assessed for each day of machine's operation in l per 100 km or l per h.

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

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

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

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

The right side of equation (4) equals to the intermediate mean unit costs $u(t_O)$ at optimum of operating time for renewal. The left side of the equation (4) equals to the intermediate immediate operation unit costs $v_P(t_O)$ at optimum of operating time for renewal. The equation describes 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 $u(t)$ it is necessary to know two basic values – renewal costs N_O (the costs of performed maintenance) and mean unit costs of operation $u_p(t)$, 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

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 a 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 (l per 100 km) 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, as shown in Fig. 1.

Relatively simple and universal data filtering can be done by setting the certain level of engine speed (motor revolution). This certain level of engine speed is a critical point when including specific consumption for further calculation. Furthermore, for each group of machines the second condition is applied for data filtering (particular machinery has its own operating state: heavy trucks – position change, excavators – on the site, dozers – move forward, etc.). Correct adjustment of the raw data filtering algorithm provides more accurate processing procedure and consequential optimal maintenance interval of a particular machine.

Specific fuel consumption is a comprehensive diagnostic signal and depends on many operational factors and therefore there is a large variance in monitored specific fuel consumptions. Linear trend is chosen because of very large dispersion of specific

Fig. 1 Correlation of specific fuel consumption and operational time of MAN TGA 35.480

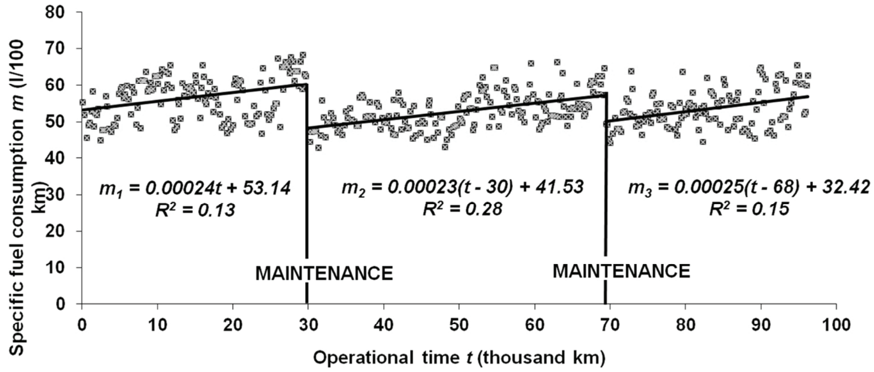


Fig. 2 Determination of engine maintenance intervals for the increase of specific fuel consumption – graphic interpretation of Table 1

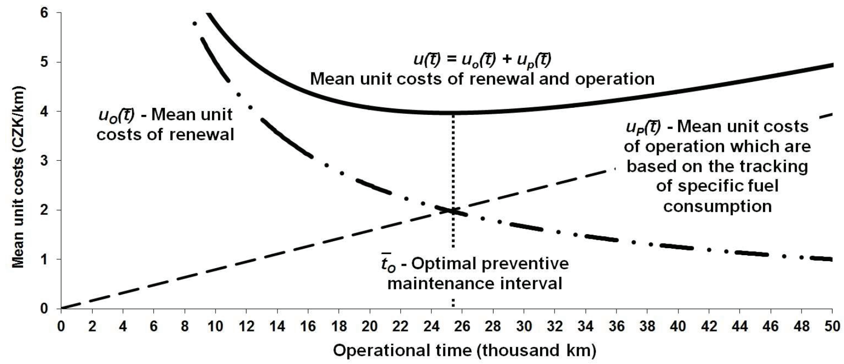


Fig. 3 Correlation of specific fuel consumption and operational time of construction machinery CAT 432E

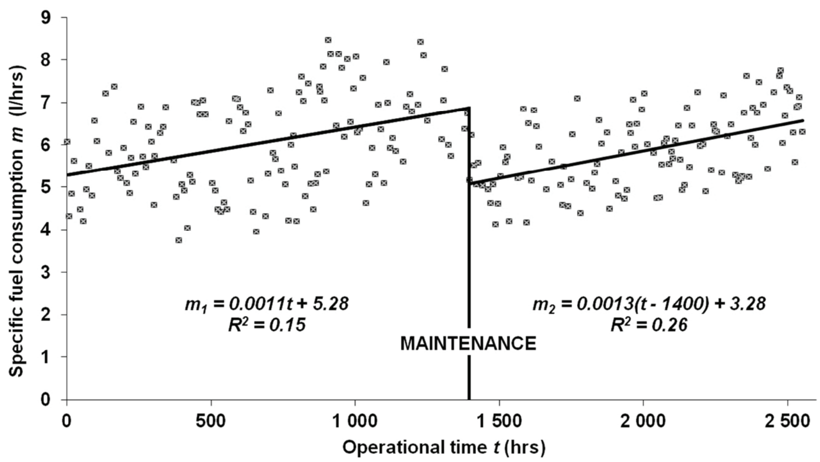
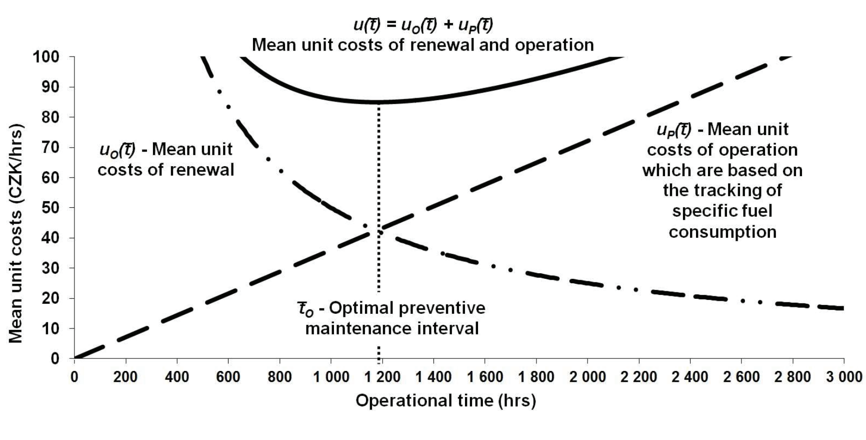


Fig. 4 Determination of maintenance intervals of construction machinery CAT 432E for the increase of specific fuel consumption – graphic interpretation



fuel consumption for each working day. Regression coefficients were similar for other types of functions, so a linear trend was chosen for simplicity. The linear trend is characterized by an increase in specific fuel consumption depending on the operational time.

DISCUSSION

The unit costs of operation $u_P(t)$ are determined by a linear trend, which is set by slope of specific fuel consumption trend and the average price of diesel fuel (32.84 CZK per l, February 2011) during vehicle operation.

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 $u_P(t)$ is linear, the local minimum of the function $u(t)$ is located at the same spot as the intersection of both forming curves $u_O(t)$ and $u_P(t)$. The specific examples of the graphic solution are shown in Figs. 2 and 4.

The costs of renewal (maintenance) for a truck MAN 35.480 8×6 are estimated at 50 000 CZK. In this particular case, the amount of 50 000 CZK represents costs of diagnostic maintenance of the motor vehicle MAN TGA 35.480. 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: 25 000 CZK per month (driver's salary) × 1.35 (deductions from wages)/20 (working days) = 1 688 CZK

(2) The financial loss due to downtime of the vehicle is calculated: 35 CZK per km (the price of the material transported by vehicle) × 220 km per day (the average distance travelled per day) = 7 700 CZK

(3) The financial loss occurred due to fuel consumed on a journey into and back: 55 l per 100 km (average specific consumption of the vehicle) × 30 km (average distance to the maintenance service and back) × 32.84 CZK per litre (average price of fuel in February 2011) = 540 CZK

(4) Costs of diagnostic maintenance = 15 000 CZK

(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.) = 25 000 CZK

This practical example shows that the optimal preventive maintenance interval is 25 187 km for vehicle MAN TGA 35.480 (see Table 1 and Fig. 2). After rounding to the nearest thousand kilometres the maintenance interval is set to 25 000 km.

For the calculated procedure, it is clear that the maintenance interval is variable and can be influenced by (1) maintenance costs and (2) function of mean unit operational costs (influenced by fuel costs).

A particular 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 a sufficient number of vehicles of the same type 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 Tables 2 and 3).

Table 2 provides data on vehicle type, number Gcom (the unit of remote control monitoring), monitored time of operation (km), average distance travelled per day, slope of linear trend of specific fuel consumption (equations in Figs. 1 and 3) and data of specified maintenance intervals $\bar{t}_O$ (km). 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. Slope of trend for vehicles MAN TGA 35.480 ranged 0.00016–0.0038. Determined optimal intervals were calculated with N_O = 50 000 CZK and average fuel costs 32.84 CZK per litre. Mean maintenance interval for vehicles MAN TGA 35.480 was 26 000 km.

A similar example is shown in Table 3. Slope of trend for vehicles MAN TGS 41.480 ranged 0.00012–0.00059. Procedure for calculation of optimal maintenance interval was the same, i.e. N_O = 50 000 CZK and average fuel costs 32.84 CZK per litre. Mean maintenance interval for vehicles MAN TGS 41.480 was 24 000 km.

The same algorithm can be used for construction machinery, but with the difference that the operational time of machines is not in travelled distance (km), but in operated hours of engine. Examples are given in Figs. 3 and 4.

Fig. 4 shows determination of optimal maintenance interval of construction machinery engine type CAT 432E. Optimal interval is set for slope of linear trend of specific fuel consumption (0.0011) based on operational time and average fuel costs 32.84 CZK per litre. Renewal costs are determined in a similar way as were determined for vehicle MAN 35.480. Optimal maintenance interval for this machine was calculated to 1176 operated hours. For better labour planning it is useful to round this number to 1200 operated hours.

Table 4 contains data about machine type, Gcom number, monitored time of operated hours, the average operated hours per day, and data of specified maintenance intervals $\bar{t}_O$ (h).

The correct determination of specific fuel consumption assumes measuring at full load, which is obviously not fulfilled in the examples. The article describes methodology for determining the optimum

Table 1. Calculation of maintenance interval of vehicle MAN TGA 35.480 8×6_for the increase in specific fuel consumption depending on the operational time with linear trend equation y = 0.00024x and fuel price 32.84 CZK per litre

Operational time (km)	Increase in specific fuel consumption (l per km)	Unit costs of operation $u_P(t)$ (CZK per km)	Unit costs of renewal $u_O(t)$ (CZK per km)	Mean unit costs of renewal and operation $u(t)$ (CZK per km)
25 185	0.060444	1.98498	1.98531	3.970289676
25 186	0.060446	1.98506	1.98523	3.970289666
25 187	0.060449	1.98514	1.98515	3.970289662
25 188	0.060451	1.98522	1.98507	3.970289665
25 189	0.060454	1.98530	1.98499	3.970289674

Table 2. Determination of the mean maintenance interval for vehicle MAN TGA 35.480

Gcom number	Average travelled distance (km per day)	Trend of slope of specific fuel consumption (–)	Determined maintenance interval t_O (km)
146	170	0.00037	20 285 → 20 000
147	227	0.00018	29 084 → 29 000
173	214	0.00023	26 497 → 26 000
174	221	0.00038	20 017 → 20 000
175	218	0.00024	25 187 → 25 000
177	206	0.00017	29 927 → 30 000
183	221	0.00016	30 848 → 30 000
Mean	211		25 777 → 26 000

Table 3. Determination of the mean maintenance interval for vehicle MAN TGS 41.480

Gcom number	Travelled distance (km)	Average travelled distance (km per day)	Trend of slope of specific fuel consumption (–)	Determined maintenance interval t_O (km)
138	36 302	198	0.00059	16 064 → 16 000
139	24 754	155	0.00055	16 638 → 17 000
140	25 573	184	0.00013	34 223 → 34 000
153	53 127	165	0.00012	35 620 → 36 000
173	27 443	160	0.00036	20 565 → 21 000
5 116	19 527	257	0.00030	22 528 → 23 000
5 045	49 621	221	0.00026	24 199 → 24 000
5 017	31 053	202	0.00036	20 565 → 21 000
Mean	33 425	193		23 800 → 24 000

Table 4. Determination of the mean maintenance interval for different construction machinery

Machine type	Gcom number	Operated time (h)	Average (h per day)	Determined maintenance interval t_O (h)
CAT CS 583C	5031	1614	6.84	1266 → 1300
KOMATSU PW 180	5041	1161	6.10	1176 → 1200
CAT 432E	5102	2551	6.39	1176 → 1200
CAT 330 CLN	5121	1051	8.67	1273 → 1300
CAT 325 C	181	1367	8.90	1082 → 1100

maintenance interval based on processing of vast amount of specific consumption data obtained from satellite monitoring, however, accurate filtering algorithm of'primary' data has not been entirely solved.

Nowadays, the authors try to improve filtering algorithm, in order to exclude data of specific fuel consumption which was measured at low engine loads. Current data sorting algorithm excludes only extreme values of consumption (e.g. idle mode), which is insufficient and ultimately regression coefficients of functions of specific fuel consumption are too low. For instance, improved filtering algorithm linked with GIS database will be able to filter fuel consumption of trucks when driving downhill, during smooth rides on the flat road or during deceleration and *vice versa* to give higher importance of consumption during acceleration and considering fully loaded truck driving uphill, etc. All of these conditions can be detected from the 'primary' data, but filtering algorithm is much more complex than the current one and its proper function has to be verified on data from dozens of machines. Improved filtering algorithm will provide a significant reduction in the variance of specific fuel consumption and thus substantial accuracy of regression coefficients the values of which have so far been debatable.

CONCLUSION

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 resolving a 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 already using 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 the variability of the 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 a precise determination of the optimal preventive maintenance interval for a specific machine, its current operational conditions, and the changes of its 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 a particular machine (calculated optimal maintenance interval deviates from the average) might be followed by a detailed diagnostics in order to determine the causes of a short maintenance interval. Proposed algorithm may contribute to better maintenance planning and consequently to economical operation of machinery.

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