Condition-based Vehicle Fleet Retirement Decision: A Case Study

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(Received on Aug.18, 2009, revised April 10, 2010)

Abstract: The vehicle replacement decision is a multi-objective optimization problem subject to the acquisition budget and government regulation constraints. This necessitates a condition-based replacement policy. In this paper, we carry out a case study of the vehicle fleet replacement problem. Based on the field data in a vehicle fleet management system, we derive a set of condition parameters for representing the health level of a vehicle. A correlation analysis is carried out to identify key condition parameters. The identified parameters are then combined into a health index. The index is useful for condition-based vehicle replacement decision.

Keywords: Vehicle fleet replacement, condition-based replacement, replacement score, health index.

1. Introduction

A transport company often owns hundreds or thousands of vehicles with a service life for about 10 – 15 years. A large number of vehicles have to be replaced each year, and hence an optimal vehicle replacement (VR for short) decision can bring to the company with substantial cost savings [1, 2].

The VR problem is a multi-objective (e.g., reliability and cost) optimization problem subject to acquisition budget constraint (due to incurring a large amount of investment) and government regulation constraint [3, 4]. The acquisition budget constraint results in a situation where the vehicles with the same age may be retired at different times [5], and the regulation constraint (aiming to reduce air pollutant emissions) results in a situation where old vehicles may be retired before their economic lifetimes have been exhausted [4].

Many methods have been developed to address the vehicle fleet replacement problem. These include fleet age profile analysis, strategic fleet acquisition and retirement model, maintenance cost trend analysis, life cycle cost analysis, average cost analysis, and the annual maintenance cost limit method [5]. In terms of the decision output, the methods roughly fall into two categories:

(a) Population-oriented methods: The decision output of a method (e.g., an economic life [6, 7]) is applicable for all the vehicles in the same age group.

(b) Individual-oriented methods: The decision output is on an individual basis so that the vehicles in the same age group can be retired at different times [2]. This necessitates the performance evaluation of each vehicle based on technical information (obtained from a vehicle inspection) and economical information (obtained from field data).
A large amount of field data in a vehicle fleet management system is available. This makes it possible to evaluate the health level of each vehicle for condition-based retirement decision. In this paper, we present an individual-oriented approach and carry out a case study, which deals with a sub-fleet in a postal vehicle fleet. The inputs include vehicle age, cumulative kilometres (CK for short), cumulative fuel consumption, and cumulative maintenance cost. The VR dates are also partially known. We derive several condition variables from the recorded parameters. A correlation analysis is carried out to identify key condition variables, which are further incorporated into a health index for condition-based VR decision.

The paper is organized as follows. Section 2 gives the case background. A preliminary data analysis is carried out in Section 3. The vehicle health index is derived in Section 4. The paper is concluded in Section 5.

2. Background

A mixed postal vehicle fleet consists of 124 vehicles. We consider a sub-fleet of 15 vehicles, which are the same type and model and started to operate on August 11, 1998. By the time that data were collected 13 vehicles had retired and 2 were still in service. The specific dates of VR are shown in Table 1.

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The government regulations for the vehicles under consideration are that the maximum age is 15 years and the vehicle with age of 10 years or over must pass some additional annual tests.

A vehicle management system started to be run on January 1, 2003, when the vehicle age was 4 years and 143 days (or initial age $t_0 = 4.3918$ years). For each vehicle the system records:

- CK reading $k(t)$ where $t$ is the vehicle age,
- Cumulative oil-consumption $l$ in litre or fuel cost $C_o = 4.5l$ in RMB Yuan, and
- Cumulative maintenance cost $C_m$ (corrective maintenance, spare part and tyre costs, etc.), which does not include the overhaul cost because the budget for overhaul (with an interval of 3-5 years) is separately considered and from a special source.

The data are updated per 6 months.

To reduce maintenance cost and improve fuel economy, the company implements an incentive policy. The main contents are:
(a) a fixed oil-consumption limit (in litre per kilometre) is set and the driver will own or pay for the difference between the actual and set oil-consumptions, and
(b) a maximum maintenance cost limit is set and the driver will pay for the excessive part (this is why the system does not include the overhaul cost).
3. Preliminary Data Analysis

3.1 Analysis of CK

Figure 1 shows \( k \) versus \( t \) (started from August 11, 1998). The dotted lines correspond to the vehicles that were retired relatively early, the fine lines correspond to the vehicles that are in operating or were retired relatively late, and the bold line is the average curve. From the figure, we have the following observations:

- The relation between the average kilometre reading and age is somewhat convex. This can be due to the behaviour to sufficiently utilize the vehicles before the retirement or due to an increase in the transport demand.

- It is noted that the lately retired vehicles have relatively large CK. This may result from the availability of a vehicle. In other words, the CK reading indirectly reflects the availability of a vehicle and hence its health level.

3.2 Analysis of Cumulative Oil-Consumption

Figure 2 shows \( C_o \) versus \( k \) (started from June 30, 2003), which is a very good proportional relation. An empiric fitting is given by:

\[
C_o(k) = 0.112908k
\]

Due to a very small dispersion, \( C_o \) is not a good measure for evaluating the health level of a vehicle.

3.3 Analysis of Cumulative Maintenance Cost

Figure 3 shows \( C_m \) versus \( k \) (started from June 30, 2003). As can be seen, \( C_m \) is relatively dispersive, and hence can be a good measure for evaluating the health level of a vehicle.

The average curve is also shown in the figure and can be approximated by

\[
C_m(k) = 0.02328k^{0.956455}
\]

The fact that power parameter is smaller than 1 implies that the maintenance cost increases with the usage slightly slowly down for large \( k \). This may be because some maintenance actions were cancelled when the VR gets close.

4. Evaluation Model for Health Level

4.1 Derived Condition Variables
4.1.1 Usage Rate $\Delta k / \Delta t$

Figure 4 shows $\Delta k / \Delta t$ versus $t - t_0$. From the figure, we have the following observations:

- Usage rate significantly varies with vehicles, implying that it is a good measure to represent the health level of a vehicle.
- The usage rate in the first half year of each year is obviously lower than the one in the second half year. This may result from two factors: schedule of maintenance actions and fluctuation of transport loads.
- The usage rate at $t - t_0 = 3.5$ is relatively low. This may be because more vehicles underwent overhauls at the time close to that.
- In the last year before the retirement, the usage rate keeps at a relatively high level. This may be because the decision-maker wants to sufficiently utilize the residual lives of the vehicles.

4.1.2 Fuel Cost Rate $\Delta C_f(k) / \Delta k$

Figure 5 shows the fuel cost rates (where $k_{0i}$ is the kilometre reading on June 30, 2003). As can be seen from the figure, a history of $\Delta C_f(k) / \Delta k$ versus $k$ can be divided into three phases: the initial low oil-consumption phase, high oil-consumption phase, and steady low oil-consumption phase. The first change from the low oil-consumption to the high oil-consumption may be due to a wear-out mechanism, and the second change from the high oil-consumption to the low oil-consumption may be due to vehicle overhauls. Since the steady low oil-consumption rates are close to each other, the oil-consumption rate is not a good measure to represent the health level of a vehicle.

4.1.3 Maintenance Cost Rate $\Delta C_m(k) / \Delta k$

Figure 6 shows the maintenance cost rates and their average curve, which can be approximated by

$$\frac{\Delta C_m}{\Delta k} = 0.03105 + \frac{k - k_{0i}}{21121.2} - \frac{\sqrt{k - k_{0i}}}{612.52}$$

(3)

The average curve has a minimum given by $k - k_{0i} = 297.26$. Since $C_m$ does not include the overhaul cost, the minimum point may correspond to overhauls. Since the maintenance cost rate significantly varies with vehicles, it is a good measure to represent the health level of a vehicle.
According to [5], an economic replacement age (which corresponds to the age from which the maintenance costs significantly increase from an equilibrium value) can be determined based on a maintenance cost trend analysis. For the current case, we let

\[ m_i(t) = \frac{1}{15} \sum_{i=1}^{15} \frac{\Delta C_m(t)}{\Delta k} \]  

\[ \Delta C_m(t) = C_m(t) - C_m(t-\Delta t) \]

Figure 5: Fuel cost rates of vehicles

Figure 6: Maintenance cost rates of vehicles

Figure 7 shows \( m_i(t) \) versus \( t \). As can be seen from the figure, the minimum point may correspond to overhauls, and \( m_i(t) \) has a significant increase after \( t \approx 9.4 \) years. As a result, the population-oriented economic replacement age is about 9.4 years. This result can be referenced for the vehicle fleet replacement decision.

4.2 VR Score and Correlation Analysis

Assume that the replacement decision is made at \( t = t_0 = 6 \) or \( t = 10.3918 \) years. Let \( s_d \) denote the replacement score of a vehicle at the decision instant. A small value of \( s_d \) implies that the vehicle has a high priority to be replaced first. For the current case, we assign a replacement score 1, 2, 3, and 4 to those vehicles that were or will be replaced in the first through fourth batches respectively. Table 2 shows the replacement scores and relevant condition variables at the decision instant. A correlation analysis between the replacement score and condition parameters will help to identify significant variables for individual-oriented replacement decision.
The correlation coefficient $r$ is a measure of strength of linear relationship between two variables \[8\]. The correlation coefficient $r(s_j, \theta)$, where $\theta$ denotes the parameters set shown in the first row of Table 2, is given in the last row of Table 2. To judge the significance of a linear correlation, we need to determine a critical value of the correlation coefficient. According to \[9\], given a correlation coefficient $r$ the significance of the linear correlation of two variables can be tested using the following statistic to transform $r$ to a Student’s $t$-value:

$$
t = r / \sqrt{1-r^2}
$$

The critical value of $t$ associated with the 80\% level, one tail, and the degrees of freedom $15-1 = 14$ is 0.8681. Namely, the critical value of $r$ is 0.6555. The correlation coefficients whose absolute values are larger than 0.6555 are: \(0.7421, 0.6914\).

This implies that $\Delta k / \Delta t$ and $\Delta C_m / \Delta k$ are positively [negatively] related to the health level of a vehicle. These are consistent with the conclusions obtained in the previous analysis.

Table 2: Replacement Scores, Condition Parameters and Correlation Coefficients

<table>
<thead>
<tr>
<th>$s_j$</th>
<th>$C_v$</th>
<th>$C_m$</th>
<th>$\Delta k / \Delta t$</th>
<th>$\Delta C_m / \Delta k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>870.369</td>
<td>64.5849</td>
<td>11.8384</td>
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</tr>
<tr>
<td>1</td>
<td>863.052</td>
<td>65.1726</td>
<td>11.0316</td>
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<td>945.683</td>
<td>68.3892</td>
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</tr>
<tr>
<td>1</td>
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<td>0.1126</td>
</tr>
<tr>
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<td>800.366</td>
<td>57.1253</td>
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<tr>
<td>1</td>
<td>899.407</td>
<td>68.0265</td>
<td>11.9023</td>
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<tr>
<td>2</td>
<td>927.284</td>
<td>67.6805</td>
<td>12.9634</td>
<td>0.1133</td>
</tr>
<tr>
<td>2</td>
<td>794.928</td>
<td>57.9362</td>
<td>11.371</td>
<td>0.1127</td>
</tr>
<tr>
<td>2</td>
<td>928.468</td>
<td>71.1522</td>
<td>10.7329</td>
<td>0.1122</td>
</tr>
<tr>
<td>2</td>
<td>917.485</td>
<td>70.1847</td>
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<tr>
<td>3</td>
<td>840.372</td>
<td>55.5791</td>
<td>7.0122</td>
<td>0.1132</td>
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<tr>
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<td>64.7073</td>
<td>12.3481</td>
<td>0.1133</td>
</tr>
<tr>
<td>4</td>
<td>936.727</td>
<td>73.7501</td>
<td>10.4026</td>
<td>0.1133</td>
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<tr>
<td>4</td>
<td>919.621</td>
<td>68.9436</td>
<td>11.131</td>
<td>0.1132</td>
</tr>
</tbody>
</table>

\(r(s_j, \theta)\) = 0.4362, 0.4124, -0.0697 $,$ 0.7421, 0.3275, -0.6914$.

4.3 Health Index

We define a health index as below:

$$
H = \alpha \frac{\Delta k}{\Delta t} - \beta \frac{\Delta C_m}{\Delta k}, \, a, b > 0
$$

where $a$ and $b$ are parameters to be determined. A large value of $H$ implies a healthy vehicle. We determine $a$ and $b$ by minimizing

$$
Y = \sum_{i=1}^{15} (H^{(i)}(a, b) - s_j^{(i)})^2
$$

Using the data in Table 2 and the above approach, we have:

$a = 0.03274, \, b = 63.42$

The health index consists of two components: $\frac{\Delta k}{\Delta t}$ and $\frac{\Delta C_m}{\Delta k}$. To examine their contributions to $H$, we look at
\[ w_a = \frac{a}{H_0} \times \frac{\Delta k}{\Delta t}, \quad w_b = \frac{b}{H_0} \times \frac{\Delta C_w}{\Delta k}, \]  

(8)

where \( H_0 = a \frac{\Delta k}{\Delta t} + b \frac{\Delta C_w}{\Delta k} \). Table 3 shows the values of \( H, w_a \) and \( w_b \). As can be seen from the table, the main contribution comes from \( \frac{\Delta k}{\Delta t} \). This is consistent with the result of the correlation analysis. It is noted:

\[ r(s_d, H) = 0.7962 > \max\{| r(s_d, \Delta k / \Delta t) |, | r(s_d, \Delta C_w / \Delta k) |\}. \]  

(9)

Namely, the correlation coefficient between the replacement score and health index is larger than the one between the replacement score and its component.

Table 3 also shows the rank number (\( R_i \)) of vehicle \( i \). A small value of \( R_i \) implies a small value of \( H \). It can be used to evaluate the consistency between the company’s replacement decision and proposed health index. Inconsistencies between the actual decision and health index occur:

(a) Vehicle 2 [Vehicle 5] should be replaced in the third [second] batch but replaced in the second [third] batch, and

(b) Vehicle 9 [Vehicle 12] should be replaced in the fourth [third] batch but replaced in the third [fourth] batch.

Considering the following facts:

- The replacement decision can be opportunity-based (e.g., an advanced replacement is possible for a relatively health vehicle if a costly preventive maintenance has to be performed shortly), and

- The inconsistencies are minor,

the proposed health index appears appropriate, and can be used to provide a relatively accurate initial ranking for VR decision.

<table>
<thead>
<tr>
<th>Vehicle ( i )</th>
<th>( H )</th>
<th>Rank, ( R_i )</th>
<th>( w_a )</th>
<th>( w_b )</th>
</tr>
</thead>
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<tr>
<td>3</td>
<td>1.6901</td>
<td>4</td>
<td>0.6930</td>
<td>0.3070</td>
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<tr>
<td>4</td>
<td>1.8595</td>
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<td>6</td>
<td>1.1953</td>
<td>3</td>
<td>0.6185</td>
<td>0.3815</td>
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<td>8</td>
<td>0.2229</td>
<td>1</td>
<td>0.5233</td>
<td>0.4767</td>
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<tr>
<td>14</td>
<td>0.9535</td>
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<td>0.3980</td>
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<td>2.3216</td>
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<tr>
<td>2</td>
<td>2.9214</td>
<td>13</td>
<td>0.8037</td>
<td>0.1963</td>
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<tr>
<td>7</td>
<td>2.0664</td>
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<tr>
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5. Conclusions

In this case study, we have presented a condition-based approach for evaluating the health level of a vehicle. The approach is useful for vehicle fleet replacement decision. The main conclusions have been:

1) The CK measure indirectly reflects the vehicle availability and hence is positively related to the vehicle health level.

2) Based on the maintenance cost trend analysis, the economic life has been estimated as 9.4 years in this case study. However, it is possible for a vehicle not to be used to its economic life due to the regulation constraint.

3) The correlation analysis is useful for identifying key condition parameters. It has been found that the replacement decision is strongly correlated with the usage rate and maintenance cost rate of a vehicle.

4) The usage rate and maintenance cost rate have been incorporated into a single health index, which is highly correlated to the replacement score. The proposed health index is useful to provide an initial ranking of vehicle health level for using in VR decision.

Currently, we are applying the proposed approach to another mini vehicle fleet to further validate the approach. To promote greater use of this approach in industry, the approach will be incorporated to a vehicle fleet decision support software package.

Acknowledgement: The authors thank Ms. M. Zhang for her work in collecting partial data used in this study. This research is supported by the Key Project of Scientific Research Fund of Hunan Provincial Education Department (No. 06A004).

References


Renyan Jiang (For his biography, please see IJPE, Vol. 6, No. 3, March 2010, page 287)

Guangcai Shi is a PG student at Changsha University of Science and Technology. He works in the direction of reliability and multi-criteria decision analysis.