 

# Reliability Analysis of an Engine Assembly Process of Automobiles with Inspection Facility

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**Abstract**

Present paper studies the reliability analysis of an engine assembly system incorporating inspection facility. The engine system consists of nine main units namely: Cylinder block, Crank shaft, Oil sump, Piston, Cylinder head gasket, Cam shaft gear, Crank shaft gear, Fuel injection pump and High pressure line. The whole system can fail due to failure of any of the units. It is also assumed that the system can fail due to catastrophic failure. The system satisfies the usual conditions like perfect repair, random variables, joint distributions etc. Each operative unit has a constant failure rate but a general repair time distribution. We transform the basic equation into integro differential equation and outline the solution procedure for a repair time distribution with an arbitrary rational Laplace transform. Various reliability characteristics such as transition state probabilities, steady state behavior, availability, reliability, MTTF and cost analysis have been obtained using a time dependent version of the supplementary variable method and Gumble-Hougaard copula methodology. Some particular cases and asymptotic behaviour of the system have also been derived to improve practical importance of the model.

**Keywords:** Supplementary variable technique, reliability, MTTF, asymptotic behaviour, Markov process.

## 1. Introduction

A system is a combination of elements forming a planetary whole i.e. there is a functional relationship between its components. The properties and behavior of each component ultimately affects the properties of the system. Any system has a hierarchy of components that pass through the different stages of operations which can be operational, failure, degraded or in repair. Failure doesn't mean that it will always be complete; it can be partial as well. But both these types affect the performance of system and hence the reliability. Goel, et al, (1985) argues that majority of the systems in the industries are repairable. The performance of these systems can influence the quality of product, the cost of business, the service to the customers, and thereby the profit of enterprises directly. Modern repairable systems tend to be highly complex due to increase in convolution and automation of systems. During the last 45 years reliability concepts have been applied in various manufacturing and technological fields. Earlier researcher (Kumar, (1992) and Kumar (1993)) discussed reliability and steady state analysis of some realistic engineering systems by using different approaches. Also Gopoalan (1982), Brown (1983), Yanez (2002) and Parthasarathy (1979) have analyzed the different approaches of standby system. Reliability techniques have also been applied to a number of industrial and transportation problems including automobile industry. Here the study is focused on the engine assembly process of automobiles.

The present paper discusses reliability analysis of the manufacturing process of a twin cylinder compression ignition engine, in which the fuel is ignited by being suddenly exposed to the high temperature and pressure of a compressed gas, rather than by a separate source of ignition, such as a spark plug, as is the case in the petrol engine. This is based on the Diesel cycle, after German engineer Rudolf Diesel. In a

 

Diesel engine instead of the air fuel mixture as in petrol engines, only air is sucked in and the fuel is injected into the cylinder in the power stroke. The engine system consists of nine main units namely: Cylinder block (CB), Crank shaft(CS), Oil sump(OS), Piston(P), Cylinder head gasket(CHG), Cam shaft gear(CSG), Crank shaft gear(CRSG), Fuel injection pump(FIP) and High pressure line (HPL). Cylinder block contains mainly two parts; they are water jackets and coolant passage. These units can fail due to various problems encountered during engine testing or engine assembly. Also the whole system can fail due to failure of any of the units. Once the system is failed due to failures of cylinder block (due to improper functioning of water jackets and coolant passage), two types of repairs are involved to repair the system i.e. constant and other is exponential, so the joint distribution is obtained using Gumble-Hougaard copula (Nelson (1999), Barlow (1965)). It is also assumed that the system can fail due to catastrophic failure. Inspection facility is provided to the system which facilitates that after failure of any of the unit, either system needs repair (which may be major, minor or overhaul) or replacement. Various reliability characteristics such as transition state probabilities, steady state behaviour, availability, reliability, Mean time to failure (MTTF) and the cost analysis have been obtained using supplementary variable technique (Gnedenko et al (1969), Chiang et al (1981), Pham, (2003)). We also perform a parametric investigation which provides numerical results to show the effects of different system parameters to the reliability and MTTF which may be helpful to managerial staff of the industry in the decision making. Assembly process and transition diagram is shown by Figs. 1 and 2 respectively. Tables 1 and 2 describe the problems encountered during engine assembly and state specification of the system respectively.

## 2. System description

*2.1* **Cylinder block (CB):** The cylinder block is a machined casting. It is cast from cast iron by sand casting and having large holes for cylinder bores. It also has water jackets and coolant passages. This is the foundation of the engine. All other units are assembled in or attached to the cylinder block.

*2.2* **Crankshaft (CS):** The crankshaft is that part of an engine which translates reciprocating linear piston motion into rotation.

*2.3* **Oil sump (OS):** The oil pump sends oil onto the bearing surfaces.

*2.4* **Piston (P):** In general, a piston is a sliding plug that fits closely inside the bore of a cylinder. Its purpose is either to change the volume enclosed by the cylinder, or to exert a force on a fluid inside the cylinder.

*2.5* **Cylinder head gasket (CHG):** Heads are cast from aluminum by die casting. They are machined to take the various parts that are attached to or installed in the heads.

*2.***6 Cam shaft and crank shaft gear (CSG and CRSG):** A gear is a toothed wheel designed to transmit torque to another gear or toothed component.

*2.***7 Fuel injection pump (FIP):** A fuel pump is an essential component on an internal combustion engine device. Fuel has to be pumped from the fuel tank to the engine and delivered under high pressure to the fuel injection system. FIP supplies fuel to the injectors at the very high pressure.

*2.***8 High pressure line (HPL):** HPL is the line which is connected from fuel tank to engine for supplying of fuel.

**Process:** The engine assembly process is described in the Figure 1.

## 3. Assumptions

(1) Initially the system is in good state.
(2) All units are connected in series.
(3) System has three states namely good, reduced efficiency and failed.

(4) It is also assumed that the system can fail due to catastrophic failure.
(5) Inspection facility is provided at the state $S_4$.
(6) When the system is failed due to oil sump defect, it is sent for minor repair.
(7) When the system is failed due to defect in FIP, it is sent for major repair.
(8) When the system is failed due to defect in CHG, it is sent for replacement of CHG.
(9) When the system is failed due to catastrophic failure, it is sent for overhaul repair.
(10) Once the system is failed due to failure of cylinder block, two types of repairs are involved to repair the system i.e. constant and other is exponential.
(11) Joint probability distribution of repair rates follows Gumbel-Hougaard copula.

**4. Notations**

| | |
|---|---|
| Pr | Probability |
| $P_0(t)$ | Pr (at time t system is in good state $S_0$) |
| $P_i(j,t)$ | Pr {the system is in failed state due to the failure of the $i^{th}$ subsystem at time t },where *i*=1,2,5,7,9,10,11,13,14,16 and *j=x, y, n, w, v, h, k, l, r, q*. |
| $K$ | Elapsed repair time, where *K= x, y, z, u, q, g*. |
| $\lambda_{FIP}$ | Failure rates of FIP or engine misfire rate. |
| $\lambda_P / \lambda_{CHG}$ | Piston seizes rate/Cylinder head gasket leaking rate or rate of overheating. |
| $\alpha_{OS_1}$ | Rate of restricted oil sump strainer or rate of low oil pressure. |
| $\alpha_i$ | Failure rate of $i^{th}$ unit, where, *i=CB, CS, CSG, CRSG, HPL.* |
| $\alpha_C$ | Catastrophic failure rate. |
| $\phi_i(k)$ | General repair rate of $i^{th}$ unit in the time interval ($k$, $k+\Delta$), where *i*= CB, CS, CSG, CRSG, HPL, P. |
| $P_4(t)$ | Pr (at time t the system is inspected at inspection section due to failure of any of the unit). |
| $\gamma_C$ | System's arrival rate for overhaul repair due to damage from catastrophic failure. |
| $\rho_{OS_1}$ | System's arrival rate for minor repair due to failure of oil sump. |
| $\mu_{CHG}$ | System's arrival rate for replacing cylinder head gasket due to leaking of *CHG*. |
| $\eta_{FIP}$ | System's arrival rate for major repair due to failure of fuel injection pump. |
| $\theta(n)$ | General minor repair rate of oil sump strainer. |
| $\xi(l)$ | General Major repair rate of fuel injection pump. |

$\psi(v)$ General replacement rate of cylinder head gasket.

$\beta(q)$ Overhaul repair rate of system due to catastrophic failure.

$\sigma_i$ General arrival rate of the $i^{th}$ unit to the inspection section for inspection, where, $i$= $OS_1$,$FIP$,$CHG$,$C$.

$K_1$, $K_2$ Revenue cost per unit time and service cost per unit time respectively.

Let $u_1 = e^x$ and $u_2 = \phi_{CB}(x)$ then the expression for joint probability according to Gumbel-Hougaard family of copula is given as

$$\phi_{CB} = \exp\left[x^\theta + [\log \phi_{CB}(x)]^\theta\right]^{1/\theta}$$

**5. Mathematical formulation of the model**

Using elementary probability considerations and limiting procedure, we obtain the following set of difference-differential equations governing the behaviour of considered system, continuous in time and discrete in space:

$$\left[\frac{d}{dt} + \alpha_{CB} + \alpha_{CS} + \alpha_{os_1} + \lambda_P + \lambda_{CHG} + \alpha_{CSG} + \alpha_{CRSG} + \lambda_{FIP} + \alpha_{HPL} + \alpha_C\right] P_0(t) =$$

$$\int_0^\infty \phi_{CB}(x)P_1(x,t)dx + \int_0^\infty \phi_{CS}(y)P_1(y,t)dy + \int_0^\infty \theta(n)P_5(n,t)dn + \int_0^\infty \psi(v)P_9(v,t)dv +$$

$$\int_0^\infty \phi_{CSG}(h)P_{10}(h,t)dh + \int_0^\infty \phi_{CRSG}(k)P_{11}(k,t)dk + \int_0^\infty \xi_{FIP}(l)P_{13}(l,t)dl + \int_0^\infty \phi_{HPL}(r)P_{14}(r,t)dr +$$

$$\int_0^\infty \beta(q)P_{16}(q,t)dq \qquad \dots (1)$$

$$\left[\frac{\partial}{\partial t} + \frac{\partial}{\partial x} + \phi_{CB}(x)\right] P_1(x,t) = 0 \qquad \dots (2)$$

$$\left[\frac{\partial}{\partial t} + \frac{\partial}{\partial y} + \phi_{CS}(y)\right] P_2(y,t) = 0 \qquad \dots (3)$$

$$\left[\frac{d}{dt} + \sigma_{OS_1}\right] P_3(t) = \alpha_{OS_1} P_0(t) \qquad \dots (4)$$

$$\left[\frac{d}{dt} + \rho_{OS_1} + \gamma_C + \eta_{FIP} + \mu_{CHG}\right] P_4(t) = \sigma_{OS_1} P_3(t) + \sigma_C P_{15}(t) + \sigma_{FIP} P_{12}(t) + \sigma_{CHG} P_8(t) \qquad \dots (5)$$

$$\left[\frac{\partial}{\partial t} + \frac{\partial}{\partial n} + \theta(n)\right] P_5(n,t) = 0 \qquad \dots (6)$$

$$\left[\frac{d}{dt}+\alpha_P\right]P_6(t)=\lambda_P P_0(t) \quad \ldots (7)$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial w}+\phi_P(w)\right]P_7(w,t)=0 \quad \ldots (8)$$

$$\left[\frac{d}{dt}+\sigma_{CHG}\right]P_8(t)=\lambda_{CHG} P_0(t) \quad \ldots (9)$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial v}+\psi(v)\right]P_9(v,t)=0 \quad \ldots (10)$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial h}+\phi_{CSG}(h)\right]P_{10}(h,t)=0 \quad \ldots (11)$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial k}+\phi_{CRSG}(k)\right]P_{11}(k,t)=0 \quad \ldots (12)$$

$$\left[\frac{d}{dt}+\sigma_{FIP}\right]P_{12}(t)=\lambda_{FIP} P_0(t) \quad \ldots (13)$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial l}+\xi(l)\right]P_{13}(l,t)=0 \quad \ldots (14)$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial r}+\phi_{HPL}(r)\right]P_{14}(r,t)=0 \quad \ldots (15)$$

$$\left[\frac{d}{dt}+\sigma_C\right]P_{15}(t)=\alpha_C P_0(t) \quad \ldots (16)$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial q}+\beta(q)\right]P_{16}(q,t)=0 \quad \ldots (17)$$

Boundary Conditions:

$$P_1(0,t)=\alpha_{CB} P_0(t) \quad \ldots (18)$$

$$P_2(0,t)=\alpha_{CS} P_0(t) \quad \ldots (19)$$

$$P_5(0,t)=\rho_{OS_1} P_4(t) \quad \ldots (20)$$

$$P_7(0,t)=\alpha_P P_6(t) \quad \ldots (21)$$

$$P_9(0,t)=\mu_{CHG} P_4(t) \quad \ldots (22)$$

$$P_{10}(0,t) = \alpha_{CSG} P_0(t) \qquad \ldots (23)$$

$$P_{11}(0,t) = \alpha_{CRSG} P_0(t) \qquad \ldots (24)$$

$$P_{13}(0,t) = \eta_{FIP} P_4(t) \qquad \ldots (25)$$

$$P_{14}(0,t) = \alpha_{HPL} P_0(t) \qquad \ldots (26)$$

$$P_{16}(0,t) = \gamma_C P_4(t) \qquad \ldots (27)$$

Initial Condition:

$P_0(0) = 1$, otherwise zero. … (28)

**6. Solution of the model**

Taking Laplace transforms of equation (1) through (27) subjected to initial condition (28) and then on solving them one by one; we obtain the following up state and down state probabilities of the system is given by:

$$\overline{P}up(s) = \overline{P}_0(s) + \overline{P}_3(S) + \overline{P}_6(s)$$

$$= \frac{1}{B(s)}\left[1 + \frac{\alpha_{OS_1}}{[s+\sigma_{OS_1}]} + \frac{\lambda_P}{[s+\alpha_P]}\right] \qquad \ldots (29)$$

$$\overline{P}_{Down}(s) = \overline{P}_1(s) + \overline{P}_2(s) + \overline{P}_4(s) + \overline{P}_5(s) + \overline{P}_7(s) + \overline{P}_8(s) + \overline{P}_9(s) + \overline{P}_{10}(s) + \overline{P}_{11}(s)$$

$$+ \overline{P}_{12}(s) + \overline{P}_{13}(s) + \overline{P}_{14}(s) + \overline{P}_{15}(s) + \overline{P}_{16}(s)$$

$$= \frac{1}{B(s)}[\ \alpha_{CB} D_{\phi_{CB}}(s) + \alpha_{CS} D_{\phi_{CS}}(s) + A(s) + \rho_{OS_1} D_\theta(s) A(s) + \frac{\alpha_P \lambda_P}{[s+\alpha_P]} D_{\phi_P}(s)$$

$$+ \frac{\lambda_{CHG}}{[s+\sigma_{CHG}]} + \mu_{CHG} D_\psi(s) A(s) + \alpha_{CSG} D_{\phi_{CSG}}(s) + \alpha_{CRSG} D_{\phi_{CRSG}}(s) + \frac{\lambda_{FIP}}{[s+\sigma_{FIP}]} + \eta_{FIP} D_\xi(s) A(s)$$

$$\alpha_{HPL} D_{\phi_{HPL}}(s) + \frac{\alpha_C}{[s+\sigma_C]} + \gamma_C D_\beta(s) A(s)\ ] \qquad \ldots (30)$$

where,

$$B(s) = s + \alpha_{CB} + \alpha_{CS} + \alpha_{OS_1} + \lambda_P + \lambda_{CHG} + \alpha_{CSG} + \alpha_{CRSG} + \lambda_{FIP} + \alpha_{HPL} + \alpha_C$$

$$- \alpha_{CB} \overline{S}_{\phi_{CB}}(s) - \alpha_{CS} \overline{S}_{\phi_{CS}}(s) - \frac{\lambda_P \alpha_P}{[s+\alpha_P]} \overline{S}_{\phi_P}(s) - \rho_{OS_1} A(s) \overline{S}_\theta(s)$$

$$-\mu_{CHG}\overline{S}_{\psi}(s)A(s)-\alpha_{CSG}\overline{S}_{\phi_{CSG}}(s)-\alpha_{CRSG}\overline{S}_{\phi_{CRSG}}(s)-\eta_{FIP}A(s)\overline{S}_{\xi}(s)$$

$$-\alpha_{HPL}\overline{S}_{\phi_{HPL}}(s)-\gamma_{C}\overline{S}_{\beta}(s)A(s) \quad \ldots (31)$$

$$A(s)=\frac{1}{[s+\rho_{OS_1}+\gamma_C+\eta_{FIP}+\mu_{CHG}]}\left[\frac{\sigma_{OS_1}\alpha_{OS_1}}{[s+\sigma_{OS_1}]}+\frac{\sigma_C\alpha_C}{[s+\sigma_C]}+\frac{\sigma_{FIP}\lambda_{FIP}}{[s+\sigma_{FIP}]}+\frac{\sigma_{CHG}\alpha_{CHG}}{[s+\sigma_{CHG}]}\right] \quad \ldots (32)$$

$$D_i(s)=\frac{1-\overline{S}_i(s)}{s}, \text{ where } i=\phi_{CB},\phi_{CS},\phi_P,\phi_{CSG},\phi_{CRSG},\phi_{HPL},\theta,\xi,\beta,\psi \quad \ldots (33)$$

$$\phi_{CB}(x)=\exp[x^{\theta}+(\log\phi_{CB}(x))^{\theta})^{1/\theta}] \quad \ldots (34)$$

$$\overline{S}_i(s)=\int_0^{\infty} i\exp[-sj-\int_0^{j} i(j)dj]dj \quad , \quad \text{where,} \quad i=\phi_{CB},\phi_{CS},\phi_P,\phi_{CSG},\phi_{CRSG},\phi_{HPL},\theta,\xi,\beta,\psi \quad .$$

$$j=x,y,w,h,k,r,n,l,q,v. \quad \ldots (35)$$

## 7. Steady state behaviour of the system

Using Abel's lemma in Laplace transforms, viz;

$$\lim_{s\to 0} s\bar{f}(s)=\lim_{t\to\infty} f(t)=f(\text{say})$$

provided the limit on the right hand side exists, the time independent operational probabilities for up and down states are obtained as follows.

$$\overline{P}up=\frac{1}{B(0)}\left[1+\frac{\alpha_{OS_1}}{\sigma_{OS_1}}+\frac{\lambda_P}{\alpha_P}\right] \quad \ldots (36)$$

$$\overline{P}_{DOWN}=\frac{1}{B(0)}[\alpha_{CB}\overline{M}_{\phi_{CB}}+\alpha_{CS}\overline{M}_{\phi_{CS}}(s)+A(0)+\rho_{OS_1}M_{\theta}A(s)+\frac{\alpha_P\lambda_P}{[\alpha_P]}M_{\phi_P}$$

$$+\frac{\alpha_{CHG}}{\sigma_{CHG}}+\mu_{CHG}M_{\psi}A(s)+\alpha_{CSG}M_{\phi_{CSG}}+\alpha_{CRSG}M_{\phi_{CRSG}}+\frac{\lambda_{FIP}}{\sigma_{FIP}}$$

$$+\eta_{FIP}M_{\xi}A(s)+\alpha_{HPL}M_{\phi_{HPL}}+\frac{\alpha_C}{\sigma_C}+\gamma_C A(s)M_{\beta}] \quad \ldots (37)$$

where,

$$B(0)=\lim_{s\to 0} B(s) \quad \ldots (38)$$

$$A(0)=\lim_{s\to 0} A(s) \quad \ldots (39)$$

$$\overline{M}_i=\lim_{s\to 0}\left\{\frac{1-\overline{S}_i(s)}{s}\right\}, \text{ where, } i=\phi_{CB},\phi_{CS},\phi_P,\phi_{CSG},\phi_{CRSG},\phi_{HPL},\theta,\xi,\beta,\psi \quad \ldots (40)$$

$$S_{\phi_i}(s)=\frac{\phi_i}{s+\phi_i}, \quad \text{where, } i=\phi_{CB},\phi_{CS,}\phi_P,\phi_{CSG},\phi_{CRSG},\phi_{HPL},\theta,\xi,\beta,\psi \qquad \ldots (41)$$

7.1 **Particular case**

A particular case is also discussed as given below:

In this case setting $\overline{S}_{\phi_i}(s)=\dfrac{\phi_i}{s+\phi_i},\forall i$ and $\overline{S}_{\phi_{CB}}(s)=\dfrac{\exp\left[x^{\theta}+[\log\phi_{CB}(x)]^{\theta}\right]^{1/\theta}}{s+\exp\left[x^{\theta}+[\log\phi_{CB}(x)]^{\theta}\right]^{1/\theta}}$ in equations (29) through (30) we get,

$$\overline{P}up(s)=\frac{1}{B_1(s)}\left[1+\frac{\alpha_{OS_1}}{[s+\sigma_{OS_1}]}+\frac{\lambda_P}{[s+\alpha_P]}\right] \qquad \ldots (42)$$

$$\overline{P}_{DOWN}(s)=\frac{1}{B_1(s)}[\frac{\alpha_{CB}}{[s+\phi_{CB}]}+\frac{\alpha_{CS}}{[s+\phi_{CS}]}+A(s)+\frac{\rho_{OS_1}A(s)}{[s+\theta]}+\frac{\alpha_P\lambda_P}{[s+\alpha_P]}\frac{\phi_P}{[s+\phi_P]}+$$

$$\frac{\alpha_{CHG}}{[s+\sigma_{CHG}]}+\frac{\mu_{CHG}\psi A(s)}{[s+\psi]}+\frac{\alpha_{CSG}}{[s+\phi_{CSG}]}+\frac{\alpha_{CRSG}}{[s+\phi_{CRSG}]}+\frac{\lambda_{FIP}}{[s+\sigma_{FIP}]}$$

$$+\frac{\eta_{FIP}}{[s+\xi]}A(s)+\frac{\alpha_{HPL}}{[s+\phi_{HPL}]}+\frac{\alpha_C}{[s+\sigma_C]}+\frac{\gamma_C A(s)}{[s+\beta]}] \qquad \ldots (43)$$

where,

$$B_1(s)=s+\alpha_{CB}+\alpha_{CS}+\alpha_{OS_1}+\lambda_P+\lambda_{CHG}+\alpha_{CSG}+\alpha_{CRSG}+\lambda_{FIP}+\alpha_{HPL}+\alpha_C-\frac{\alpha_{CB}\phi_{CB}}{[s+\phi_{CB}]}$$

$$-\frac{\alpha_{CS}\phi_{CS}}{[s+\phi_{CS}]}-\frac{\alpha_P\lambda_P}{[s+\alpha_P]}\frac{\phi_P}{[s+\phi_P]}-\frac{\rho_{OS_1}A(s)\theta}{[s+\theta]}-\frac{\mu_{CHG}\psi A(s)}{[s+\psi]}-\frac{\alpha_{CSG}\phi_{CSG}}{[s+\phi_{CSG}]}-\frac{\alpha_{CRSG}\phi_{CRSG}}{[s+\phi_{CRSG}]}$$

$$-\frac{\eta_{FIP}\xi}{[s+\xi]}A(s)-\frac{\alpha_{HPL}\phi_{HPL}}{[s+\phi_{HPL}]}-\frac{\gamma_C A(s)\beta}{[s+\beta]} \qquad \ldots (44)$$

**9. Results and discussion:**

In this paper we calculated availability, reliability, MTTF and cost function for an engine assembly process of automobile system by employing supplementary variables technique and Gumble-Hougaard copula methodology. Also, we have computed asymptotic behavior and a particular case to improve practical utility of the system. Numerical computation with its graphical illustration has been mentioned in the end to highlight important results of the study. Figure 3 shows the values of availability function at different time points. Analysis of Figure 3 reveals that availability of considered system decreases catastrophically in the beginning but after $t$ =3, it decreases in a constant manner. The Figure 4 shows the trends of reliability of the system with respect to time when all the failures and repair rates have some fixed values. From the graph we can conclude that the reliability of the system decreases smoothly with passage of time. Next, we study the effect of various parameters on the MTTF. The observation of Figure 5 reveals that M.T.T.F. of the complex system decreases in a constant manner as the value of cylinder block failure rate ($\alpha_{CB}$), crank shaft failure rate ($\alpha_{CS}$) and cam shaft gear failure rate ($\alpha_{CSG}$) increase. An interesting phenomenon is seen that mean operating time to failure is same for $\alpha_{CS}$ and $\alpha_{CSG}$. Figure 6 shows the variation of MTTF for piston seize rate. An unusual fact is obtained here that as the value of $\lambda_P$ increases the MTTF is also increases. By the examination of Figure 7 we can conclude that the MTTF for engine misfire rate ($\lambda_{FIP}$) and catastrophic failure rate ($\alpha_C$) decreases constantly. Figure 8 shows the values of cost function at various time points for different values of service cost. Critical examination of Figure 8 yields that increasing service cost leads decrement in expected profit.

Thus, for a given set of different parameters one can estimate the availability, reliability, MTTF and profit analysis of the complex system at any time *t* well in advance, to forecast the behavior in operation of such a complex system.

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**Table 1 State specification table**

| States | Description | System State |
|---|---|---|
| $S_0$ | When the system is in fully operational condition. | G |
| $S_1$ | When the system is in failed state due to failure of water jacket and cooling passage of cylinder block. Here two types of repairs are involved to repair the system. So joint probability distribution is obtained using copula. | $F_R$ |
| $S_2$ | When the system is in failed state due to the failure of crank shaft. | $F_R$ |
| $S_3$ | When the system is in reduced efficiency state due to the problem of low oil pressure (restricted sump strainer) i.e. the strainer is not clear. | D |
| $S_4$ | When the system is in inspection. | G |
| $S_5$ | When the system is in minor repair due to defect in oil sump. | $M_R$ |
| $S_6$ | When the system is in reduced efficiency state due white exhaust i. e. the piston is beginning to seize. | $D_R$ |
| $S_7$ | When the system is in failed state due to failure of piston. | $F_R$ |
| $S_8$ | When the system is in failed state due to overheating or leakage of cylinder head gasket. | F |
| $S_9$ | When the cylinder head gasket is replaced by new one. | $F_R$ |
| $S_{10}$ | When the system is in failed state due to failure of cam shaft gear. | $F_R$ |
| $S_{11}$ | When the system is in failed state due to failure of crank shaft gear. | $F_R$ |
| $S_{12}$ | When the system is in failed state due to incorrect FIP timing. | F |
| $S_{13}$ | When the system is in major repair due to defect in fuel injection pump. | $MJ_R$ |
| $S_{14}$ | When the system is in failed state due to the failure of high pressure line. | $F_R$ |
| $S_{15}$ | When the system is in failed state due to catastrophic failure. | F |
| $S_{16}$ | When over haul repair of the system is going on due to catastrophic failure. | $F_R$ |

$F_R$=Failed state under repair, F=Failed state, G=good state, D= Degraded, $D_{R=}$Degraded under repair, $M_R$=Minor repair, $MJ_R$=Major repair.

**Figures**

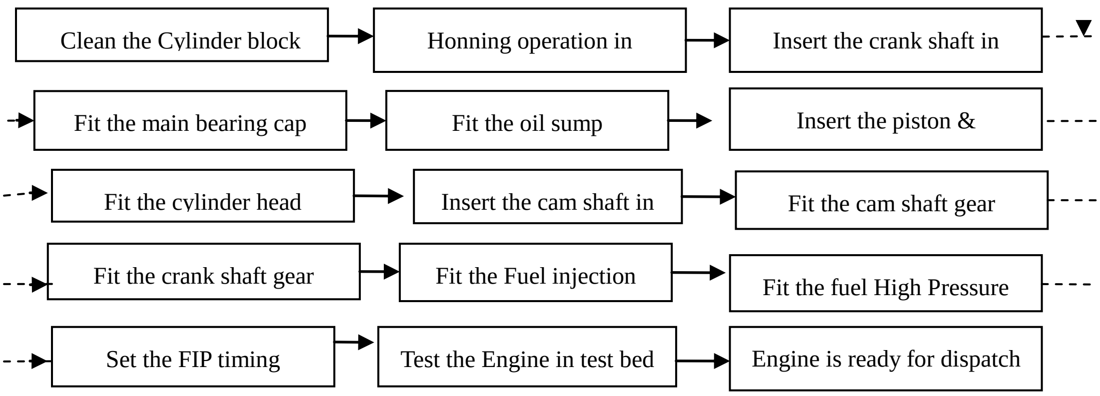


**Figure 1: Engine assembly process diagram**

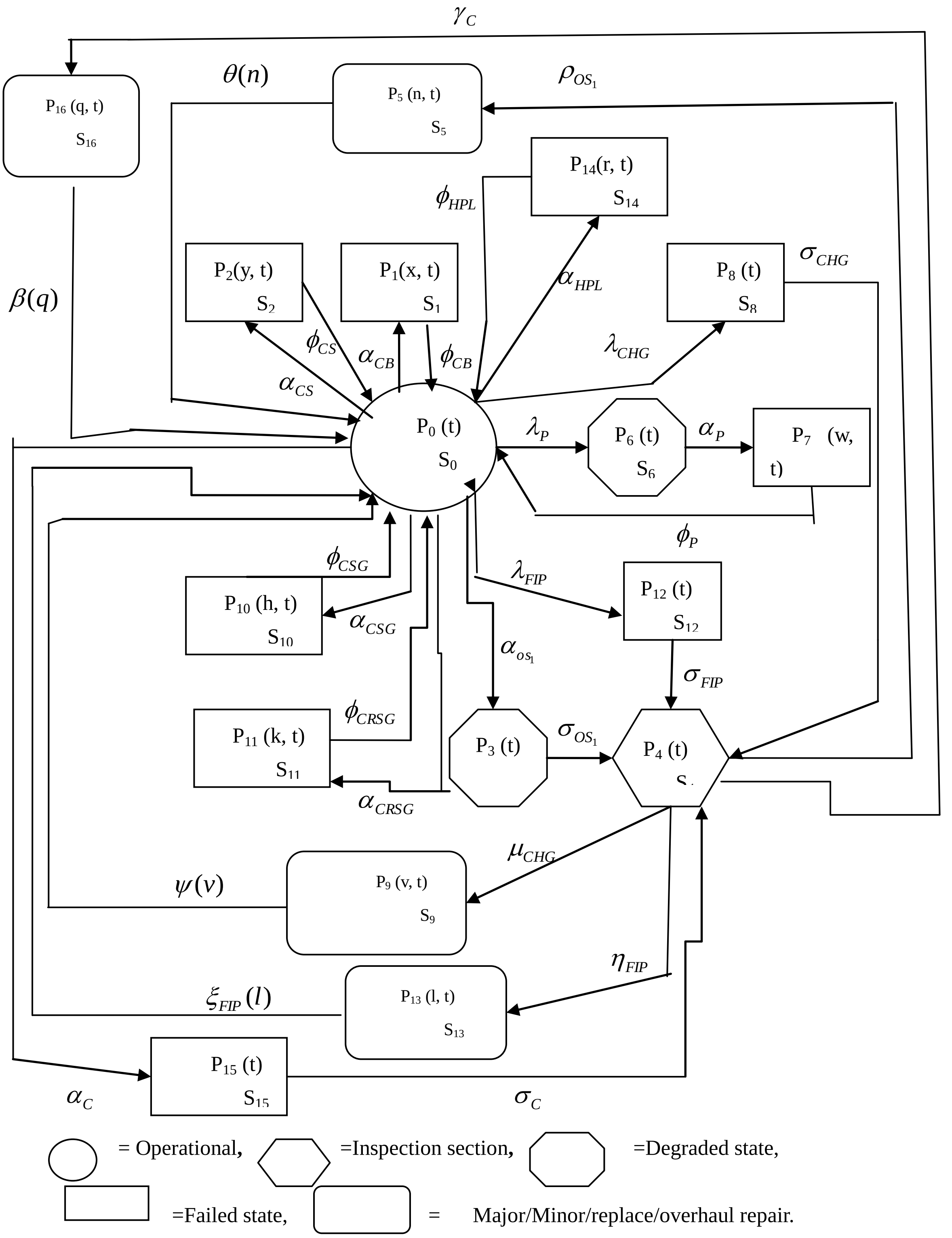


**Figure 2: Transition state diagram**

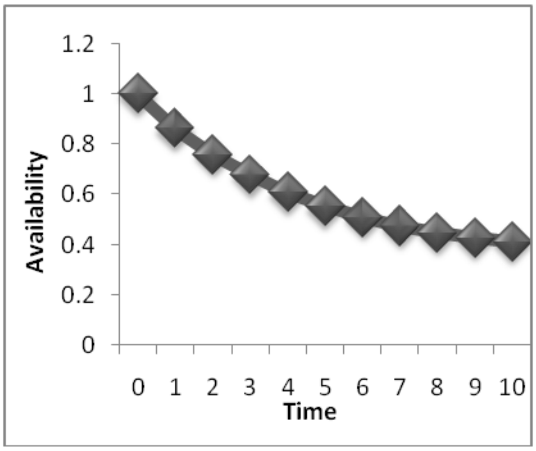


**Figure 3: Availability Vs Time**

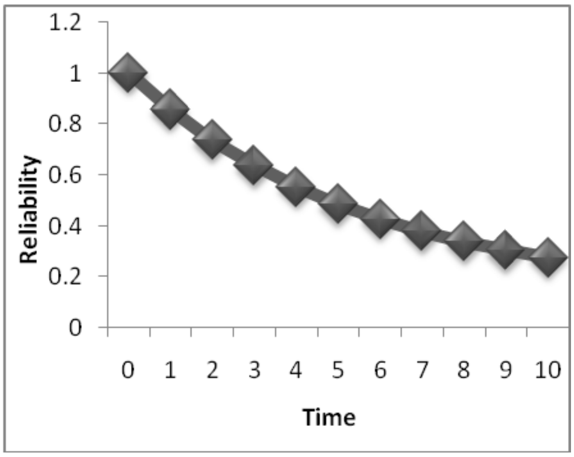


**Figure 4: Reliability Vs Time**

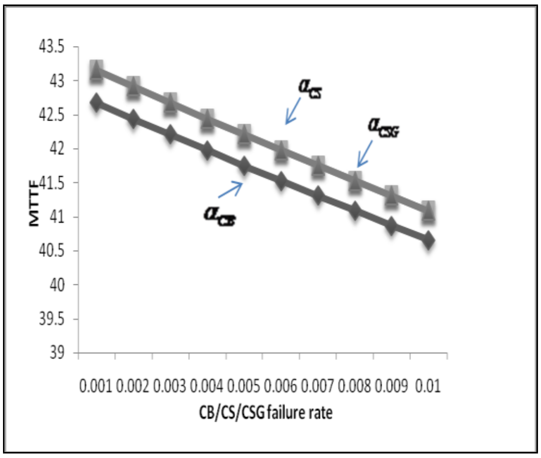


**Figure 5:** MTTF Vs $\alpha_{CB}, \alpha_{CS}, \alpha_{CSG}$.

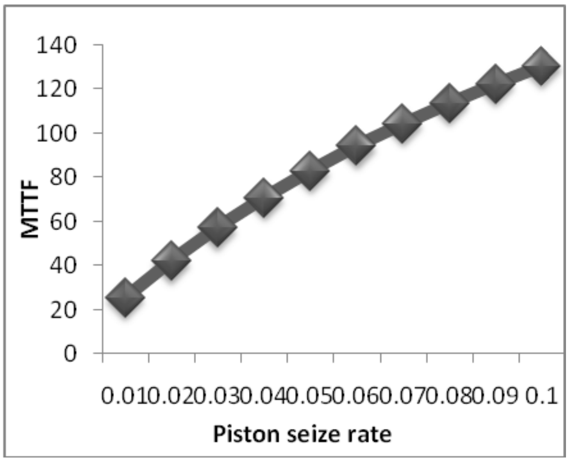


**Figure 6:** MTTFVs $\lambda_P$

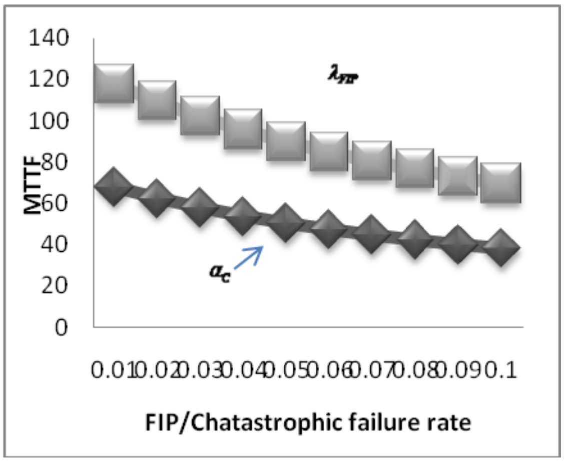


**Figure 7: MTTF Vs** $\lambda_{FIP}, \alpha_C$

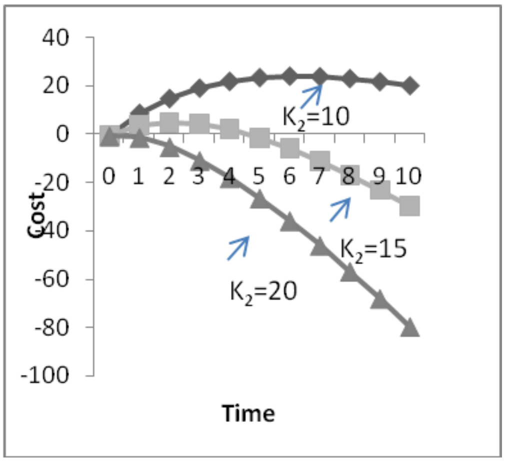


**Figure 8: Cost vs. Time**

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