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Article

Optimal maintenance through statistical failure data in a garbage fleet. A case of study

Mantenimiento óptimo mediante datos de fallas estadísticas en una flota de camiones de basura. Un caso de estudio

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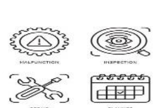
Abstract

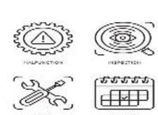
The main focus of this study is to obtain an optimal maintenance to a garbage fleet. To achieve this, statistical failure is examined, analyzed and compared with the actual costs that the city council pays for the maintenance service. This article presents a proposal for analyzing failure data from a fleet of KENWORTH [M-T370] garbage fleet. The objective is to identify and implement strategies that reduce operating costs and extend the vehicle lifespan through optimal maintenance.

Objetives	Methodology	Contribution
To obtain an optimal maintenance study based on statistical failure data using a mathematical model. 	Statistical Failure data analysis. Sensitivity analysis. Comparison of actual costs with those obtained from the model.	To obtain an optimal maintenance analysis applied to a garbage fleet in order to identify and implement strategies that minimize maintenance costs.

Failure, Optimal maintenance, Industrial planning

Resumen

El enfoque principal de este estudio es obtener un mantenimiento óptimo para una flota de vehículos de basura. Para lograr esto, se examinan y analizan estadísticamente las fallas, y se comparan con los costos reales que el ayuntamiento paga por el servicio de mantenimiento. Este artículo presenta una propuesta para analizar los datos de fallas de una flota de vehículos de basura KENWORTH [M-T370]. El objetivo es identificar e implementar estrategias que reduzcan los costos operativos y prolonguen la vida útil de los vehículos mediante un mantenimiento óptimo.

Objetivos	Metodología	Contribución
Obtener un estudio de mantenimiento óptimo basado en datos estadísticos de falla utilizando un modelo matemático. 	Estadística deAnálisis de datos de fallas. Analisis de sensibilidade. Comparacion de costos reales con los obtenidos con el modelo matematico.	Obtener un analisis de mantenimiento óptimo aplicado a una flota de camiones de basura para identificar y aplicar estrategias que permitan minimizar los costos de mantenimiento.

Falla, Mantenimiento óptimo, Planeación industrial

Area: Development of strategic leading-edge technologies and open innovation for social transformation

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Introduction

The maintenance consists of a series of techniques that seek to keep equipment and facilities in operation for as long as possible to achieve maximum availability and performance. The maintenance is expected to reduce the frequency of unscheduled interruptions. The maintenance currently plays a fundamental role in any industrial activity and represents an important challenge for the productivity and competitiveness of companies. In this sense, utilities seek to optimize the maintenance of their equipment by maximizing availability and minimizing costs. The maintenance ensures component and system reliability, in addition to increasing system capacity through the use of more reliable components. Reliability and cost are two important aspects of a vehicle fleet. [Muñoz Choque, 2021].

In [Cordero & Estupiñan 2018]. fleet maintenance is the process of keeping all vehicles of an organization in good working order so that they can be used safely and efficiently, which produces better results in vehicle tests and inspections conducted by the Federal Motor Carrier Safety Administration [*FSMA*], responsible for regulating truck safety. This article presents the results obtained from the application of Reliability Centered Maintenance [*RCM*] strategies to the fleet of hydro tank trucks. The maintenance is also based on probabilistic models; the implementation of maintenance management software [*CMMS*]; performance indicators [*RAMS*], statistical distribution, etc.

In [Conde Luna & Mosquera Muñoz, 2022], the lack of management in fleet maintenance; the lack of records format and the lack of control over incidents related to fleet maintenance result in low availability and maintainability of vehicles. The results of quantitative scientific strategies applied to industrial maintenance are presented. The methodology is applied to components to determine historical failures and statistical maintenance data, establishing protocols and roadmaps for maintenance management. The application of the procedure is evaluated by means of indicators [*RAMS*]. Using reliability tools; failure mode analysis; effects [*FMEA*] and root cause analysis [*RCA*].

The results of this research include an evaluation of the maintenance function, allowing the identification of equipment, critical components and subsystems, as well as the quantification of their economic impact and providing the basis for effective technical and training actions.

In [Carrasco & Rodrigo, 2014], proposes the determination of a maintenance policy applied to a fleet of mining trucks, where part of the basis of the model is based on the time of use. The methodology used considers a marginal cost criterion, which is incurred by the maintenance activities of the components analyzed.

The objective of the model corresponds to the minimization of costs considering the variation due to the part of the general costs where the system is considered in series.

Only the costs considered for fixed maintenance activities are taken, which are calculated based on the cost of the equipment of each of the units, considering the time and cost of the workshop, which are obtained from a linear function for all periodic maintenance [*MP*] interventions, given by the equation: $C_{FIJO} = C_{Transporte} + C_{Detención}$. Part of the variable costs per component consists of spare parts and inputs of the activity performed specifically given by a periodic maintenance [*MP*] or the cost of corrective maintenance [*MC*]. Time, emergencies, spare parts and availability of each unit of heavy machinery are taken into account.

To define a finite time horizon, a maintenance policy is established, which is defined by an interval between *MP* and time [*t*]. With a probability of 50% the reliability of the equipment will be deficient, defining the mean time between interventions and the mean time between failures [*MTBF*], obtaining the following cost equation: *MTBF [T] T Xr [t] + [1 - R [T] x ∫ R [t] dt = T > 0*. The result of the research is the minimization of maintenance costs in the equipment and the increase of the number of interventions, giving as a solution the optimal maintenance.

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In [Melchor Hernández, Rivas Dávalos, Coria & Maximov, 2014], a model is presented to optimize the maintenance policy of electrical equipment. Historical data on failures in this equipment are used. The two-parameter Weibull distribution function and scheduled maintenance are used, a cost function is minimized to determine the optimal maintenance. The objective is to minimize the cost function, determining the period [T] and the number of times [N] the equipment should be maintained.

The model used is based on an imperfect maintenance policy with minimum repairs for each statistical failure.

The total expected cost includes the costs of: minimum repair, scheduled maintenance and the replacement cost of the equipment, where the replacement cost will always be greater than or equal to the scheduled maintenance.

Model

The Municipality of Cordoba, Veracruz, Mexico; is an public institution in charge of the welfare of the citizens. Among its functions are maintaining the cleanliness of the city, through garbage collection. It also has a maintenance workshop divided into five different sections [mechanical, electrical, lubrication, machining and welding] responsible for repairing the aforementioned equipment. Repairs performed in the workshop are based on the various subsystems of the truck [engine, hydraulic system, electrical system, suspension and braking system]. There are currently 33 garbage collection vehicles, of which 20 are under repair and 13 are in operation for 33 routes in the city.

The model used in this research is based on the failure history of the 33 vehicles, with a sample of 24 years. In order to determine the optimal maintenance, the optimal number and the optimal period of maintenance is sought.

The cost of current corrective maintenance is used as a basis [$M\ C_R$]. The corresponding minimum repair costs C_1 and scheduled cost C_2, are considered constant within the mathematical model, since they reflect the current values of the maintenance costs incurred in the workshop.

On the other hand, the replacement cost C_3 is the only one that changes, because this type of corrective maintenance is performed in external workshops. Therefore, its value depends on the used material and labor costs of the external workshop. The current internal maintenance cost is related to the number of workers involved in the execution of the maintenance tasks. As The maintenance costs increase, the number of personnel required to perform the activities increases proportionally. For estimation purposes in this study, the approximate minimum monthly salary in Mexico for the year 2025, which is $12,000 pesos per worker, is considered as a reference.

The distribution function [1] is used to represent the statistical failure behavior of the equipment [Melchor Hernández, Rivas Dávalos, Coria & Maximov, 2014].

$$\lambda(t,T)=\left[\frac{T}{TBASE}\right]^{\beta}\frac{\beta}{\alpha}\left[\frac{t}{\alpha}\right]^{\beta-1} \quad [1]$$

Where:

t= Statistical time of failure.
T= Optimal maintenance period.
*T*BASE= Maintenance programmed by the company.
β= Shape parameter.
α= Scale parameter.
λ [*t,T*]= Probability function of failure occurrence.

The model used is based on an imperfect maintenance policy with minimal repairs. Equation [2] is used to obtain the total cost of optimal maintenance.

$$C(N,T)=\frac{1}{NT}\left[C_1\sum_{j=0}^{N-1}\int_0^{NT}\lambda(t,T)dt+(N-1)C_2+C_3\right] \quad [2]$$

Where:

C_1 = Minimum repair cost.
C_2 = Scheduled maintenance cost.
C_3 = Equipment replacement cost.
N= Number of optimal maintenance.
T= Period of optimal maintenance.
C[N,T]= Cost of optimal maintenance.
λ [*t,T*]= Probability function of failure.

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Methodology

To obtain the optimal maintenance, the failure history of the 33 vehicles with a sample of 24 years [from 1998 to the beginning of 2023] will be used for their analysis and classification.

Table 1 shows the data corresponding to the 33 vehicles analyzed; the first column presents the chronological order in which the 33 vehicles were put into service, starting with the first vehicle that entered into operation and concluding with the last vehicle; the second column indicates the year in which each vehicle entered into operation; the third column corresponds to the year in which the vehicles were retired, or if not, whether they remain in operation; and the fourth column presents the years in which the unit was in operation or if not, whether it remains in operation.

Box 1

Table 1

Table of vehicle fleet data [KENWORTH M-T370].

Fleet of vehicles [KENWORTH M-T370] on service and withdrawn.			
Vehicle unit	**Number of year of service**	**Number of year of retirement**	**Time of service[Years]**
Vehicle 1	1998	2022	24
Vehicle 2	1998	2022	24
Vehicle 3	1998	2022	24
Vehicle 4	1998	2022	24
Vehicle 5	2000	2023	23
Vehicle 6	2000	2023	23
Vehicle 7	2000	2023	23
Vehicle 8	2000	2023	23
Vehicle 9	2002	2023	21
Vehicle 10	2002	2023	21
Vehicle 11	2002	In operation	In operation
Vehicle 12	2006	In operation	In operation
Vehicle 13	2006	In operation	In operation
Vehicle 14	2006	In operation	In operation
Vehicle 15	2009	In operation	In operation
Vehicle 16	2011	In operation	In operation
Vehicle 17	2011	In operation	In operation
Vehicle 18	2011	In operation	In operation
Vehicle 19	2011	In operation	In operation
Vehicle 20	2014	In operation	In operation
Vehicle 21	2014	In operation	In operation
Vehicle 22	2014	In operation	In operation
Vehicle 23	2014	In operation	In operation
Vehicle 24	2019	In operation	In operation
Vehicle 25	2019	In operation	In operation
Vehicle 26	2019	In operation	In operation
Vehicle 27	2019	In operation	In operation
Vehicle 28	2019	In operation	In operation
Vehicle 29	2019	In operation	In operation
Vehicle 30	2019	In operation	In operation
Vehicle 31	2019	In operation	In operation
Vehicle 32	2019	In operación	In operation
Vehicle 33	2019	In operation	In operation

Source: Own elaboration

Table 2 shows the failure classification data of the retired vehicles. Column 1 presents the classification of the vehicles starting from the first vehicle that entered service [1998] to the last vehicle that entered service [2002]. Column 2 shows the cumulative years of the vehicles.

For example: row 1 and 2 show vehicles 1-4 that have 1 and 2 cumulative years of service [1998-1999], respectively, and so on, successively until the sample is reached. Column 3 shows the number of accumulated failures in the years of operation, and finally column 4 shows the number of vehicles retired per year.

From 2002 onwards, the 10 vehicles accumulate consecutive years [5, 6,..., years] of service; from the year 2022 onwards, the first retirements occur as shown in row 21. In this row 2 vehicles are retired, as well as in row 23, 3 vehicles are retired, for a total of 5 retired vehicles shown in row 24.

Box 2

Table 2

Table arranged from historical failure data N=24 years and 10 retired vehicles.

Fleet of vehicles [KENWORTH M-T370] on service and withdrawn			
Sample [10 vehicles]	**Number of years accumulated**	**Number of accumulated failures**	**Number of retirees**
Vehicle 1-4	Year 1	7	0
Vehicle 1-4	Year 2	15	0
Vehicle 1-8	Year 3	29	0
Vehicle 1-8	Year 4	34	0
Vehicle 1-10	Year 5	42	0
Vehicle 1-10	Year 6	42	0
Vehicle 1-10	Year 7	47	0
Vehicle 1-10	Year 8	49	0
Vehicle 1-10	Year 9	49	0
Vehicle 1-10	Year 10	52	0
Vehicle 1-10	Year 11	52	0
Vehicle 1-10	Year 12	67	0
Vehicle 1-10	Year 13	67	0
Vehicle 1-10	Year 14	76	0
Vehicle 1-10	Year 15	78	0
Vehicle 1-10	Year 16	86	0
Vehicle 1-10	Year 17	86	0
Vehicle 1-10	Year 18	89	0
Vehicle 1-10	Year 19	94	0
Vehicle 1-10	Year 20	94	0
Vehicle 1-10	Year 21	97	2
Vehicle 1-8	Year 22	57	0
Vehicle 1-8	Year 23	57	3
Vehicle 1-5	Year 24	29	5
Total	24	1416	10

Source: Own elaboration.

To perform the sensitivity analysis of the model performance, 3 case studies were established in 3 subsystems [engine, electrical system, hydraulic system] of the 5 divided subsystems of the vehicle fleet.

Table 3 shows the ordered failure data of the engine subsystem. Column 1 shows the subsystem of the analyzed area [engine]. Column 2 shows the number of failures occurring for each year, with a cumulative total of 602 failures and; column 3 presents the frequency with which each number of failures is repeated per year.

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Box 3

Table 3

Area test [engine], the total failures and failure times are taken in the period in which the sample is repeated.

Area engine	Number of failures	Number of times the number of failures in the cumulative year matched
Failures in the engine area of the 10 vehicles in the 24 years accumulated	2	1
	9	1
	18	1
	25	2
	26	2
	35	2
	40	1
	44	3
	47	2
	51	2
	54	1
	60	3
	64	1
	67	1
	60	1
Total	**602**	**24**

Source: Own elaboration

The first case study was designed considering the following real costs applied in the engine subsystem. C_1:$20,000, C_2:$30,000 all in Mexican pesos. The value of the cost of C_3: varies as follows: $250,000, $300,000, $350,000, $400,000, $450,000. In addition, the interval of the current initial maintenance time To=12 months is considered.

Table 4 presents the optimal values of: T, N, the optimal maintenance cost and, the current corrective maintenance cost $[M\ C_R]$. Case 1 shows a $C_3/\ C_2$ ratio of $8.33, so the model suggests maintenance [T] every 14.11 months. For case 3, the $C_3/\ C_2$ ratio is $11.66, so the model suggests giving maintenance [T] every 13.01 months. For the last case, the $C_3/\ C_2$ ratio is $15.00, so the model suggests maintenance [T] every 12.28 months. As can be seen, the more expensive the $C_3/\ C_2$ ratio, the more frequent the maintenance. Furthermore, the optimal maintenance cost obtained by the model is lower in all cases than the actual corrective maintenance.

Box 4

Table 4

Case 1.- Engine subsystem results. $C[N,T]$ for different cost values C_1, C_2, C_3.

Case	*Cost* $M\ C_R$	*C [N,T]*	*N*	*T*	C_1	C_2	C_3
1	48,000	38,006	17	14.11	20,000	30,000	250,000
2	48,000	39,722	21	13.50	20,000	30,000	300,000
3	48,000	41,197	25	13.01	20,000	30,000	350,000
4	60,000	42,496	29	12.61	20,000	30,000	400,000
5	60,000	43,661	33	12.28	20,000	30,000	450,000

The second case study presents the actual costs of the electrical system subsystem. C_1: $3,500, C_2: $20,000, the value of C_3: varies as follows: $45,000, $60,000, $70,000, $85,000, $90,000, for each case respectively. In addition, the initial current maintenance time interval To=12 months is considered.

Table 5 presents the optimal values of: T, N, the optimal maintenance cost and, the current corrective maintenance cost $[M\ C_R]$. Case 2 shows a $C_3/\ C_2$ ratio of $3, so the model suggests maintenance [T] every 32.93 months. For case 4 the $C_3/\ C_2$ ratio is $4.25, so the model suggests maintenance [T] every 30.44 months. For case 5 the $C_3/\ C_2$ ratio is $4.5, so the model suggests maintenance [T] every 30.00 months. As can be seen, the more expensive the $C_3/\ C_2$ ratio is, the more frequent maintenance is required. In addition, the optimal maintenance cost obtained by the model is lower in all cases than the actual corrective maintenance.

Box 5

Table 5

Case 2.- Electrical subsystem results. $C[N,\ T]$ for different cost values C_1, C_2, C_3.

Case	*Cost* $M\ C_R$	*C [N, T]*	*N*	*T*	C_1	C_2	C_3
1	12,000	9,159	4	35.05	3,500	20,000	45,000
2	12,000	9,762	6	32.93	3,500	20,000	60,000
3	12,000	10,191	8	31.50	3,500	20,000	70,000
4	12,000	10,555	10	30.44	3,500	20,000	85,000
5	12,000	10,707	11	30.00	3,500	20,000	90,000

Source: Own elaboration

The third case study was designed considering the following real costs applied in the hydraulic system subsystem. C_1: $9,500, C_2: $18,500. The value of C_3 varies as follows $69,000, $99,000, $120,000, $130,000, $136,000, for each case respectively. In addition, the interval of the current initial maintenance time To=12 months is considered.

Table 6 presents the optimal values of: T, N, the optimal maintenance cost and, the current corrective maintenance cost $[M\ C_R]$. Case 1 shows a $C_3/\ C_2$ ratio of $3.72, so the model suggests maintenance [T] every 18.32 months. For case 5 the $C_3/\ C_2$ ratio is $6.87, so the model suggests maintenance [T] every 12.52 months. As can be seen, the more expensive the $C_3/\ C_2$ ratio is, the more frequent maintenance is required. In addition, the optimal maintenance cost obtained by the model is lower in all cases than the actual corrective maintenance.

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Box 6

Table 6

Case 3.- Hydraulic subsystem results. $C[N, T]$ for different values of costs C_1, C_2, C_3.

Case	*Cost* $M\ C_R$	*C [N, T]*	*N*	*T*	C_1	C_2	C_3
1	24,000	23,602	3	18.32	9,500	18,500	69,000
2	36,000	29,780	6	14.41	9,500	18,500	99,000
3	36,000	31,497	7	13.66	9,500	18,500	120,000
4	36,000	32,947	8	13.04	9,500	18,500	130,000
5	48,000	34,251	9	12.52	9,500	18,500	136,000

Source: Own elaboration

Results

As can be seen, the current corrective maintenance cost $[M\ C_R]$ is equivalent to the monthly cost of the number of workers required. As the replacement cost C_3 increases, the number of personnel required to perform maintenance activities also increases proportionally. For example in Table 4, the current corrective maintenance cost $[M\ C_R]$ is $48,000 equivalent to 4 workers. In comparison to case 5 which presents a cost of $60,000 corresponding to 5 workers. This difference is due to the fact that the replacement cost in case 5 is higher, which implies a greater demand for personnel to perform the maintenance activities. In the case of Table 5, it can be observed that in all cases the current corrective maintenance cost $[M\ C_R]$ is $12,000 equivalent to the monthly cost of 1 worker, this is due to the fact that the replacement cost of the 5 cases is not too high, which implies a lower demand for personnel to perform the maintenance activities. The optimal maintenance cost obtained is lower in all cases, for example in Table 5 the model recommends modifying the revision interval from 12 to 30.00 months, which allows reducing the total maintenance cost from $12,000 to $10,707.

Conclusions

In this work, an analysis was presented to determine the optimal moment to apply maintenance according to the critical areas of the equipment, as well as the appropriate frequency of intervention, considering the costs associated with maintenance. The analysis focused on three subsystems [electrical system, hydraulic system and engine] by using a mathematical model, it is possible to interpret the behavior of the failures throughout the operating period.

The results obtained allow establishing objective criteria for making decisions related to preventive maintenance, the optimal number of maintenance and the optimal period, with the purpose of minimizing the total costs and maximizing the reliability of the vehicle fleet.

Availability of data and materials

The Matlab software was used, which is an element analysis tool that helps us to applied the optimal maintenance of a vehicle garbage fleet through the analysis of failure data.

Declarations

The authors of this article declare that they have no conflicts of interest. They have no competing financial interests or known personal relationships that could have influenced the work presented in this article.

Author contribution.

Hernandez-Sanchez, Yrwin Hair: Contributed with the idea of the project, to the study of the documented research for publication, supported in the writing of the article and data analysis.

Melchor-Hernández, César Leonardo: Elaborated the structure of the article, reviewed the writing and analyzed the data.

Calderón-Palomares, Luis Antonio: Contributed to the study of the documented research for the publication, as well as to the data analysis.

Jiménez-Solis, Miguel Ángel: Carried out the research design, defined the type of research and participated in writing the article.

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Abbreviations

AMFE	Failure mode and effects analysis.
CMMS	Computerized maintenance management system.
FSMA	Federal Motor Carrier Safety Administration.
MC	Corrective maintenance.

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M Cr	Corrective maintenance Real.
MO	Mean time.
MP	Periodic maintenance.
MTBF	Mean time between failures.
N	Number of time.
N[M-Op]	Optimal maintenance number.
NT	Maintenance cost number.
RAMS	Reliability, availability, maintainability, and safety.
RCA	Root cause analysis.
RCM	Reliability-centered maintenance.
T	Time.

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Antecedents

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