Failure Analysis and Warranty Modelling of Used Cars

Abstract

Reliability is an important aspect of product perception and manufacturers are compelled to take corrective actions on the items failing within the warranty period. Automotive manufacturers are being exposed to significant operating costs as a result of warranty claims affecting an individual unit or mandatory (sometimes voluntary) recalls affecting a batch. Underlying principles of warranty modelling are built by considering both subjective issues and objective constraints such as competition, quality, and performance under the goal of achieving desired levels of reliability and cost in a balanced manner. This paper reviews the warranty cost models with an emphasis on the failure analysis of used vehicles. Expected warranty costs are calculated by taking into account the age, usage, and maintenance data of the product in question. Failure intensities and characteristics are identified in order to propose a policy that highlights the trade-off between the cost and the warranty length. A case study on a popular brand's initiation of factory certified pre-owned program for the local automobile market of Turkey is presented in detail.

Key Words: Warranty cost; reliability; second-hand car

1. Introduction

Reliability is one of the most important product attributes for consumers in making their selections among different alternatives [1]. Researchers showed a great deal of interest towards the studies involving reliability modelling and failure analysis of automotive industry related products. Schneider and Tibbetts [2] evaluates engine reliability by analyzing warranty data. Root-cause analysis of the ignition system used in Ford during eighties is presented by Thomas *et al.* [3] and then later on several warranty provision scenarios of these units are discussed in Pecht [4]. Surface defects on car paint are investigated by Torkar and Godec [5] to conclude the problems in galvanic zinc coating process. Naikan and Kapur [6] propose a procedure for reliability analysis of lubricating oil used for car engines. In case where the product of interest is a car, consumers' perception of reliability simply turns into a function of warranty features such as the policy length and coverage. By definition; warranty of a product is a bounding contract offered by the producer to the consumer to replace or to repair a faulty item, or to refund the whole or a part of the price of the product to the consumer when the product fails within the stated time period [7].

In today's fiercely competitive environment, length of the offered warranty period is gone out of being a legal obligation (minimum of 2-3 years depending on the country of sale) and has become one of the most important marketing tools and design parameters of the producers. Several big automobile manufacturers recently extended their warranty lengths and used this action as a primary driving force in their advertisements campaigns. For example; Hyundai extended its offer of 5-year unlimited kilometer warranty to 10-year/100,000 mile in all their products offered in the United States [8], where Honda extended its 3-year/100,000 kilometer warranty to 6-year/150,000 kilometer in all its cars for sale in Turkey [9]. Note that far eastern manufacturers tend to have longer warranty periods as opposed to their European counterparts. However, their mandatory periodical services also tend to be more frequent. (i.e.

10,000 kilometers as opposed to 15,000 kilometers) As a result of these warranty length and coverage initiatives, automotive industry handles more than 100 million warranty claims each year [10].

Used car sales have the lion's share of the vehicle market in the countries where transportation by car is the primary choice of travel simply because of geographical, demographical, and infrastructural reasons. In the United States alone, for the calendar year 2008, a total of 11 million new cars (passenger cars and light trucks) were sold in contrast to the sale of 36.5 million used cars from both dealers and end users [11]. The drastic rise of used car sales can be better observed in developing countries where car ownership goes out of being a luxury and starts becoming a basic necessity for day to day activities. According to statistics from China Automobile Dealers Association, used car sales have risen from 252,000 units in 2010 to 3,72 million units in 2010 [12]. Another momentum of increasing sales within used vehicles may also be observed for purchases taking place through an authorized dealer rather than buying directly from the owner. Purchases of used cars made through the dealers improve the transactional security as well as the trust in the quality of the used product. These vehicles are usually offered in a separate sales department under the name of factory or dealer certified pre-owned vehicle and they are subject to different sales terms and conditions than their brand new counterparts in terms of warranty limitations, claims and duration. As opposed to brand new cars, which have legal warranty policy obligations, major policy terms of the pre-owned vehicles are determined individually by dealers or companies to maximize the attractiveness of the product while minimizing the warranty costs.

Researchers showed great deal of interest in the modelling and analysis of warranty characteristics of products that are offered to customers with no prior aging effect. An earlier study by Blischke and Scheuer [13] handles the problem from a financial point of view by modelling warranty costs as a function of lifetime distribution and estimate expected number of replaced items. Nguyen and Murthy [14] also estimate expected total warranty costs along with expected number of returned items for repair. An in depth taxonomy of warranty policies that are present in the literature is also provided in early 90's [15]. Several recent studies involve extensions of these warranty models to cover the pre-owned product domain. Chattopadhyay and Murthy [16] discuss 3 different cost sharing warranty policy options for second-hand products based on specific parts exclusion, limit on individual cost, and limit on individual and total cost. 2D policies that take into account warranty criteria in a dual manner, such as year and mileage of a car warranty, have also been investigated by Chattopadhyay and Yun [17]. Recent literature also includes investigations on the optimal reliability improvement of used items under warranty protection through initiatives such as upgrade action and screening test [18, 19, and 20].

The remainder of the paper is organized as the following. Next section introduces warranty cost models, their general assumptions and suitable extensions for application to the second-hand car market. Afterwards, reliability models necessary for estimating the parameters of the fitted density are given along with an illustration on the data set gathered from an authorized dealer operating in the Turkish market. Finally, the paper concludes with a discussion on the benefits, limitations and future research perspectives.

2. Warranty Cost Models

Estimation of warranty costs by dealers is becoming more and more important each day as they try to lengthen their warranty periods in order to outpace their competitors. Several critical factors, such as the age and maintenance history of the used product has to be taken into account precisely so that unpredicted costs faced during the warranty period could be avoided. From this perspective, warranty should be modeled as a function of the reliability of the product in question. Policies offered for second-hand products, lifetime warranties, service contracts and extended warranty coverage's are the branches of long term warranty policy models that take into account such critical factors [21]. The branch of policies that cover second-hand product domain has 4 distinct types [16, 22, and 23].

Free Repair (or replacement) Warranty (FRW) policy puts the burden to the dealer (or manufacturer). Under FRW policy, dealer repairs (or replaces) the failed product with no cost reflected to the owner. This kind of policy can be either renewing (policy period resets itself after repair just as the product purchased at that time) or non-renewing (original policy period continues after repair). Non-renewing FRW policy is an industry standard for car dealers with the exception where certain exclusions are made.

These exclusions may best be characterized by a second type of policy, Cost Sharing Warranty (CSW), where cost of repair is distributed among the dealer and the owner. Since the foundations of cost sharing can vary, this policy family can further be categorized with respect to the exclusion of certain parts or by limits on repair costs. Excluded parts of CSW policy offered to a used car may not be clear instantly since these days almost all factory or authorized service installed parts (except wearing and tearing parts such as glass, tires, interior, suspension geometrics etc.) are covered unless a user negligence is present.

Third branch of used product warranties are policies that pay rebate. Under Rebate Warranty (RW), seller refunds back to the buyer some proportion of the sale price (as a function of age) if the product fails during the warranty period. Short term money back guarantees or long term rebates offered through the replacements of failed product fall into this category of policies and found a wide application within products offered by retailers selling durable consumer products.

Last type of policy suitable for used products are Hybrid Warranties (HW) involving the combination of policies previously mentioned. Under HW, warranty period is divided into 2 parts where a FRW policy is imposed during the initial phase that is followed by a RW for the rest of the warranty coverage. Discounts offered for the replacement of parts or whole product are the typical kind of rebates offered under this policy.

As an industry standard, warranty policies for automobiles do not offer a rebate perspective for the failures occurring from factory installed parts. Replacement of the whole product (the car itself) is also an event that rarely happens as a result of a lawsuit or out of courtesy for covering product reputation impact (must be authorized by the factory). For these reasons, only FRW policy with repairs and CSW policy with part exclusions are found to be applicable to used car industry.

2.1 General Model Assumptions

Assumptions given below regarding the claim and failure characteristics are made for both of the models discussed here.

- Previous maintenance history and usage frequency of the vehicles are not taken into account. Only the age of the car at time of sale is considered.
- A claim is received for each and every failure and honored by the dealer.
- Failures are statistically independent. None of the previous repairs have an impact on the failure characteristic of the car. Also the used cars are sold without any upgrade action.
- Assessment time of the claim is negligible.
- Repair and part procurement time of the car is negligible (with respect to age).
- Cost of each repair is a random variable and varies.

2.2 Free Repair Warranty (FRW)

FRW policy states a length of warranty period, w, during which the dealer is obligated to repair the failures free of charge to the new buyer. If the vehicle is at age a at the time of the sale, the number of claims over the specified warranty period w can be shown as $N(w,a)$;

where these claims occur according to a Poisson process with the intensity function $\Lambda(t)$. Intensity function can also be described as time dependent failure rate of the item and can be shown as;

$$\Lambda(t) = \frac{f(t)}{R(t)} \tag{1}$$

where $R(t)$ is the reliability of the item and calculated as $1 - F(t)$. Then, the expected number of claims is calculated from the following.

$$E[N(w,a)] = \int_a^{a+w} \Lambda(t)dt \tag{2}$$

If the average warranty cost of each repair during the period *w* is $\bar{c}$ then, the expected warranty cost can be given as

$$E[c(w,a)] = \bar{c}\int_a^{a+w} \Lambda(t)dt\,. \tag{3}$$

2.3 Cost-Sharing Warranty (CSW)

CSW policy allocates the relevant costs separately to the dealer and buyer based on the coverage principles stated explicitly. In a similar fashion to FRW policy, the expected warranty cost of each repair during the period *w* is utilized as $\bar{c}_D$ and $\bar{c}_B$ both for dealer and buyer. Expected warranty costs of the dealer and the buyer is then calculated by evaluating the intensity functions of each group individually over the length of the warranty period starting from age *a*. For the dealer;

$$E[c_D(w,a)] = \bar{c}_D\int_a^{a+w} \Lambda_D(t)dt \tag{4}$$

and for the buyer;

$$E[c_B(w,a)] = \bar{c}_B\int_a^{a+w} \Lambda_B(t)dt\,. \tag{5}$$

Note that, every component has to be designated to the dealer or buyer as the cost carrier based on the exclusions made in the warranty coverage. From dealer's unilateral point of view, FRW and CSW policies produce identical cost burden since repairs under warranty coverage will only be charged as a cost to the dealer.

3. Reliability and Warranty Analyses

This pilot study is based on a single dealer of a European brand so that geographical contributions and technological know-how effects on the failure mechanism can be isolated. In order to have sufficient data, a top selling 4-door compact sedan model is taken into consideration for the analysis. Although this model is available on the market with many optional features; body style, assembly process and framing are to be the same in all. Effects of the additional features such as sunroof, alloyed rims, leather interior etc. are assumed to be unbiased. Dealer acquires the used cars thru trade-ins and usually from the first owner who originally bought the car from the very same dealer. The brand under investigation is currently offering 3-year bumper to bumper warranty to their brand new products (A minimum of 2-year limited coverage is enforced by local laws for all manufacturers). Only the vehicles still operating under the original warranty are to be considered for an extended warranty policy under certified pre-owned program (Under this extension, an extra time period is added to the original warranty length at the expense of the dealer). This approach is crucial for the bookkeeping of failure history in details and making sure that first owner hasn't taken service from an unauthorized service center on the grounds that the car's warranty policy will be void. Dealer's service center has provided the maintenance history of vehicles that has claimed warranty for the second half of 2009. Periodical service histories are also collected in order to be aware of possible acute problems or owner complaints transmitted during the specified odometer reading intervals. No recurrent problem has been observed during this period. All the vehicles are found to be under the mileage limitations of the original factory warranty. Also no voluntary or mandatory recalls are announced for the series sold in the Turkish market. Electrical system, mechanical (engine), breaking and steering (B&S), transmission, and body (surface) finishing are the 5 different failure classes chosen for categorization of warranty claims.

[Table 1 about here]

Data at hand is singly censored where *n* successive failure times $t_1 < t_2 < ... < t_n$ occur in a prespecified system time. Our service center records show that there had been 41 valid warranty claims during this 6-month period (test time in days). Fulfillment time of the claims are regarded as the failure time of the vehicle (vehicle time in days) and treated as the parametric variable on Table 1. Weibull distribution is generally assumed to be the underlying distribution in hardware failures since it is very flexible in characterizing both increasing and decreasing failure rate. In order to validate Weibull assumption, certain parametric test measures are taken into account. Empirical distribution of failure times, which are derived through median ranking, are plotted against theoretical distribution $F(t)$ of Weibull model on Figure 1.

[Figure 1 about here]

Least squares method is also utilized to estimate the linear relationship that provides best Weibull fit. Results highlight a significant fit along with an R-squared (coefficient of determination) value of 0.96 also supporting the Weibull assumption for failure times.

Hypothesis testing approach based on the Maximum Likelihood (ML) estimates of the shape parameter, $\hat{\beta} = 1.86$, and scale parameter, $\hat{\theta} = 330{,}36$ days (0.905 years), is carried at 0.05 significance level by Chi-square goodness of fit and Mann's tests to further validate whether the failure times are Weibull distributed or not. Results are found as following:

Chi-Square test → H_0 : failure times are Weibull
H_1 : failure times are not Weibull
degrees-of-freedom = 4
$test - \chi^2 = 6.44 < critical - \chi^2_{0.05,4} = 9.49$
Do not reject H_0. Weibull assumption holds

Mann's test → H_0 : failure times are Weibull
H_1 : failure times are not Weibull
degrees-of-freedom = 40, 40
$test - M = 0.31 < critical - F_{0.05,40,40} = 1.693$
Do not reject H_0. Weibull assumption holds

As a natural result of every repairable system, the failure rate decreases by the end of each testing cycle. However, failure rate remains constant during subsequent testing. The probability distribution of the number of failures during a cycle can be approximated by non-homogeneous Poisson process given as,

$$\Lambda(t) = \frac{\beta}{\theta}\left(\frac{t}{\theta}\right)^{\beta-1} \quad \text{where } t, \beta, \theta > 0 \quad . \qquad (6)$$

This model can be proved to be extra convenient as its intensity function is found to be identical to the form of a Weibull failure rate function (also the power law process) where $F_{weibull}(t) = 1 - e^{-\left(t/\theta\right)^{\beta}}$. Consequently, the following intensity function can also be used in situations where the times between failures do not follow Weibull distribution.

$$\Lambda(t) = \frac{f(t)}{R(t)} = \frac{dF(t)/dt}{1 - F(t)} = \frac{\beta}{\theta}\left(\frac{t}{\theta}\right)^{\beta - 1} \tag{7}$$

Since our underlying distributions is found to be Weibull, we may proceed by utilizing the ML estimates of shape and scale parameters, on the intensity function, in order to calculate the expected warranty costs for various settings of a and w. Based on these setting and the associated intensity function, expected warranty cost domain of the dealer for FRW is illustrated in Table 2 as a cost matrix. Average cost ($\bar{c}$) is estimated from the reported cost of each claim fulfillment and found to be \$163.75 during the test interval. This estimate is based on \$40/hour of labor cost (combination of administrative and technical labor) in half hour increments and the cost of all necessary parts (replacement and/or rectification). Since the dealer only considers cars still operating under original warranty, upper bound for past age (a) of the car is restricted to 3-years.

[Table 2 about here]

Second-hand cars offered by the authorized dealers usually have price tags higher than the average book value. As mentioned previously, consumer's desire for transactional security and convenience makes these vehicles attractive even though they are more expensive. These and many other buyers would like to pay an extra premium in order to buy a second-hand vehicle with extended warranty service. Sedan car under investigation has an average price of \$25,000 - \$17,500 in the second-hand market of Turkey (aged 1-3 years) depending on optional features, accessories etc. Dealer may choose to sell the factory certified cars with a 5 to 10% higher than the average market value price tag in order to compensate for expected warranty service costs while protecting value/price ratio. Warranty cost domain is plotted on Figure 2 as a response surface and yields an ideal extended warranty period of 18 to 24-

months with a maximum expected warranty cost of $2406 which can be compensated by dealer's price premium.

[Figure 2 about here]

4. Conclusions

Extended warranty services offered in the sale of second-hand cars has become a major marketing tool in the recent years. Nowadays, almost all authorized dealers facilitate used car sale departments in order to liquidate the inventories build up by trade-inn initiatives. This study illustrates the modelling of expected warranty costs as an important decision support tool in the construction of feasible warranty durations while limiting the long term warranty costs to an acceptable level.

Analyses conducted here are based on a data set gathered from a best selling sedan model of a European brand and reflects the failure mechanism of this certain model. However, extended warranties offered by dealers are usually applied to all models with identical terms, conditions and length unless it's a commercial vehicle or it is sold as part of a fleet contract. For this reason, further analysis covering all model spectrum of the brand with data gathered from multiple service points has to be implemented along with trade-off analysis between models. Also, if there are any special terms regarding to the repair policy, such as deductibles, these provisions need to be taken into account. Some used car extended warranties apply deductibles on a per visit basis meaning that every time you bring your car into the service shop for a warranted repair, you must pay a deductible.

Changes in the suppliers of crucial parts may also take place throughout the lifecycle of a specific model or between models. This effect must be taken into account during failure classification so that it can be identified as an assignable cause (if present) for all parts supplied by the same supplier. This identification can be achieved by obtaining the failure data as periodical snapshots of the service records and analyzing them simultaneously. Such group of failures must be evaluated at a macro level by the higher management. Voluntary or mandatory recalls and their associated budget can cover the cost of these failures.

Apart from the analysis of expected warranty cost, variations from the mean cost should also be analyzed. Variance of the warranty cost may especially be important for long term financial and risk planning activities such as hedging and insurance. Validation and verification of the losses incurred by the dealer, as a result of the extended warranty length, should further be analyzed as new claim data becomes available from the sold used cars. Such error analysis and derivation of variance terms for the associated warranty cost models seem promising research directions.

References

1. Garvin, D.A. (1987) “Competing in the Eight Dimensions of Quality”, Harvard Business Review, 87(6), pp.101-109.

2. Schneider, R.W. and Tibbets, D.R. (1983) Assessing product reliability from warranty data, Society of Automotive Engineers Technical Paper Series 831200.

3. Thomas, D., Ayers, K. and Pecht, M. (2002) “The "Trouble Not Identified" Phenomenon in Automotive Electronics”, Microelectronics Reliability, 42(4-5), pp. 641-651.

4. Pecht, M. (2006) “Establishing a Relationship between Warranty and Reliability”, IEEE Transactions on Electronics Packaging Manufacturing, 29(3), pp. 184- 190.

5. Torkar, M. and Godec, M. (2003) “Surface defects in car paint from recombination of atomic hydrogen”, Engineering Failure Analysis, 10(3), 325-328.

6. Naikan, V.N.A. and Kapur, S. (2006) “Reliability modelling and analysis of automobile engine oil”, Proc. IMechE Part D: J. Automobile Engineering, 220(2), pp. 187-194.

7. S. Chukova, R. Arnold and D.Q. Wang (2004) “Warranty analysis: An approach to modelling imperfect repairs”, International Journal of Production Economics, 89(1), pp. 57-68.

8. Hyundai Motor Company, USA; http://www.hyundaiusa.com/assurance/america-best-warranty.aspx

9. Honda Motor Company, Turkey; http://www.honda.com.tr/orijinal_urun_garantisi. aspx

10. Smith, B.C. and Miller, R.T. (2005) “The Warranty Process Flow within the Automotive Industry: An Investigation of Automotive Warranty Processes and Issues”, Center for Automotive Research

11. U.S. Department of Transportation, Bureau of Transportation Statistics, National Transportation Statistics; http://www.bts.gov/publications/national_transportation_statistics/

12. China Automobile Dealers Association Statistics; http://chinaautoweb.com/2011/03/used-car-sales-in-china-increased-15-to-3-72-million-in-2010/

13. Blischke, W.R., Scheuer, E.M. (1975), "Calculation of the cost of warranty policies as a function of estimated life distributions", Naval Research Logistics Quarterly, 22(4) pp.681-96.

14. Nguyen, D.G., Murthy, D.N.P. (1984), "A general model for estimating warranty costs for repairable products", IIE Transactions, 16(4) pp.379-86.

15. Blischke, W.R., Murthy, D.N.P. (1992), "Product warranty management – I: a taxonomy for warranty policies", European Journal of Operational Research, 62(2), pp.127-48.

16. Chattopadhyay, G.N., Murthy, D.N.P. (2001), "Cost Sharing Warranty Policies for Second-hand Products", International Transactions in Operational Research, 8(1), pp. 47-60.

17. Chattopadhyay, G.N. and Yun, W. (2006), "Modeling and analysis of warranty cost for 2D-policies associated with sale of second-hand products", International Journal of Reliability and Applications, 7(1), pp. 71-77.

18. Chattopadhyay, G.N., Murthy, D.N.P. (2004), "Optimal Reliability Improvement for Used Items Sold with Warranty", International Journal of Reliability and Applications, 5(2), pp. 47-58.

19. Saidi-Mehrabad, M., Noorossana, R. and Shafiee, M. (2010) "Modeling and analysis of effective ways for improving the reliability of second-hand products sold with warranty", International Journal of Advanced Manufacturing Technology, 46(1-4), pp. 253-265.

20. Shafiee, M., Chukova, S., Yun, W.Y. and Niaki, S.T.A. (2011) "On the investment in a reliability improvement program for warranted second-hand items", IIE Transactions, 43(7), pp. 525-534.

21. Chattopadhyay, G.N., Rahman, A. (2008), “Development of lifetime warranty policies and models for estimating costs”, Reliability Engineering & System Safety, 93(4), pp. 522-529.

22. Chattopadhyay, G. and Murthy, D.N.P. (2000) “Warranty cost analysis for second-hand products”, Journal of Mathematical and Computer Modelling, 31(10), pp. 81-88.

23. Chukova, S., Johnston, M.R. (2006), “Two-dimensional warranty repair strategy based on minimal and complete repairs”, Mathematical and Computer Modelling, 44(11-12), pp. 1133-1143.

Nomenclature

a	age of the car at the time of the sale
$\bar{c}$	average repair cost per repair
$\bar{c}_D$	average repair cost of the dealer per repair
$\bar{c}_B$	average repair cost of the buyer per repair
CSW	cost sharing warranty
FRW	free repair (replacement) warranty
$f(t)$	probability density of failure mechanism
$F(t)$	cumulative probability density of failure mechanism
$E[N(w,a)]$	expected number of claims
$E[c(w,a)]$	expected warranty cost
ML	maximum likelihood
$R(t)$	reliability function
$test-\chi^2$	test statistic value of goodness-of-fit test
$test-M$	test statistic value of Mann's test
w	warranty length
β	shape parameter of Weibull distribution
$\Lambda(t)$	intensity function
θ	scale parameter of Weibull distribution

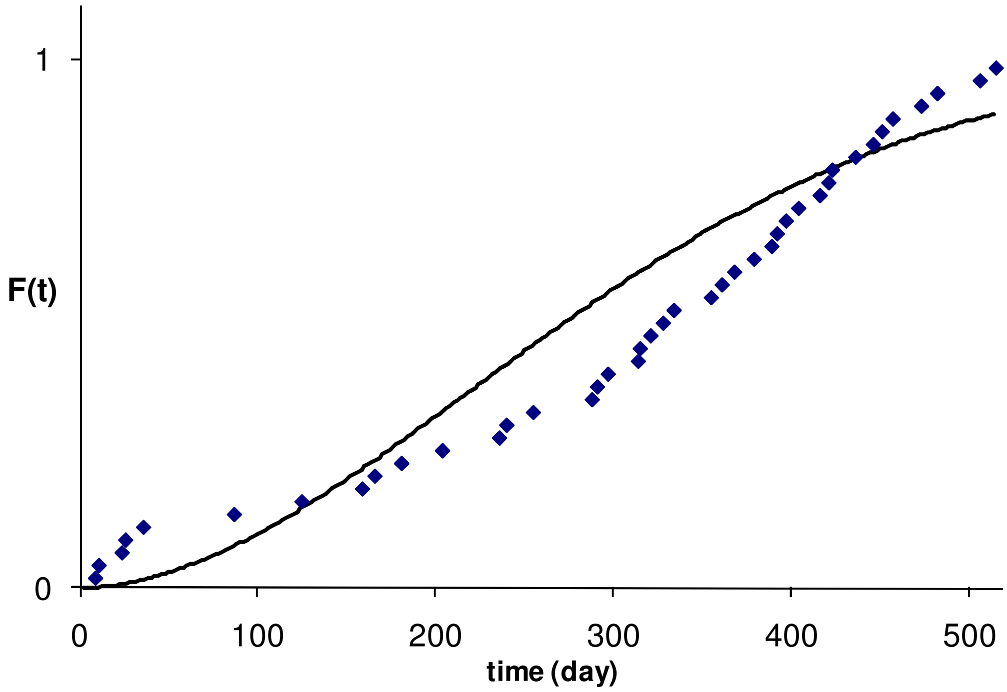

Figure 1. Weibull plot of failure times

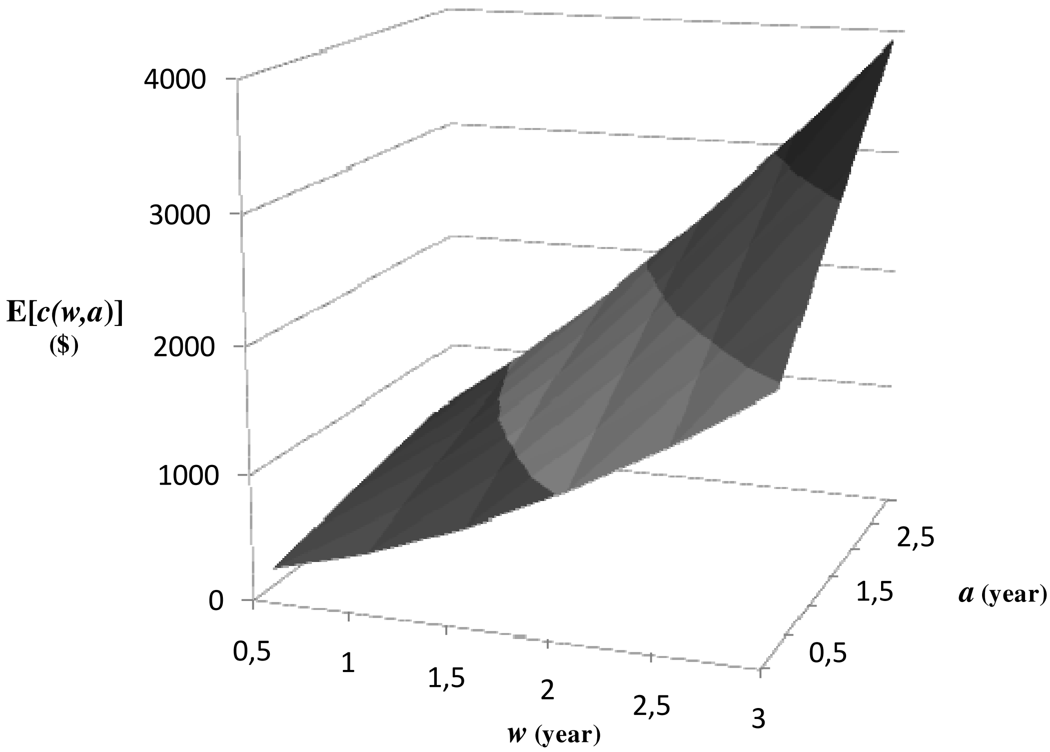

Figure 2. Surface plot for expected warranty cost versus
Age of the Car (a) and Warranty Length (w)

Table 1. Failure Data

Claim	Test Time	Vehicle Time	Failure Class	Cost ($)
1	3	321	Mechanical	122
2	10	87	Electrical	83
3	12	404	Transmission	358
4	15	166	Mechanical	260
5	19	379	Electrical	45
6	24	204	Body	100
7	31	473	Mechanical	60
8	34	9	Transmission	66
9	35	181	Mechanical	755
10	40	436	B&S	45
11	42	392	Transmission	160
12	47	451	B&S	169
13	51	288	Mechanical	370
14	55	159	Mechanical	144
15	62	11	B&S	205
16	71	26	Electrical	45
17	76	361	Electrical	60
18	79	421	Mechanical	338
19	83	515	B&S	87
20	89	24	Body	100
21	92	236	Mechanical	125
22	94	334	Electrical	320
23	99	36	Mechanical	84
24	106	446	B&S	45
25	113	506	Mechanical	145
26	120	297	Body	100
27	123	315	Mechanical	87
28	132	389	Mechanical	435
29	137	423	B&S	245
30	139	125	B&S	136
31	142	291	Electrical	83
32	143	368	Transmission	60
33	149	255	Electrical	130
34	154	328	Mechanical	75
35	158	416	Mechanical	109
36	160	240	Transmission	475
37	165	482	Transmission	160
38	167	397	Mechanical	60
39	172	314	Mechanical	154
40	177	457	B&S	45
41	181	355	Electrical	69

Table 2. Expected warranty cost

	a					
w	0.5	1	1.5	2	2.5	3
0.5	143	222	296	367	436	504
1	364	518	663	804	940	1074
1.5	660	885	1100	1308	1510	1708
2	1028	1322	1604	1877	2144	2406
2.5	1464	1825	2173	2512	2842	3166
3	1968	2395	2808	3210	3603	3989