Warranty Cost Savings of LED Signal Lights

Application Note 1155-1

NOTE:
Solid State Light Emitting Diodes (LEDs) will outlive their incandescent equivalents in exterior automotive applications by tens of thousands of hours. For a 250,000 vehicle program using LED rear signal lighting, the expected warranty savings will be $2.2 M during the four year warranty period.

Summary

LED lamps have a significantly higher reliability than incandescent bulbs. The potential savings in warranty repair when using LEDs instead of incandescent bulbs is highly attractive for automotive signal lamps – especially Center High Mount Stop Lamps (CHMSL) and rear combination lamps.

Seventeen popular 1998 U.S. models of cars and light trucks (listed in Appendix A) were used to establish a database for the number and types of incandescent bulbs used in the signal lights. This database was used to evaluate the economic advantage of LEDs over current lighting technology. Life cost modeling was done for three-year/36 K mile and four-year/50 K mile warranty programs. Copies of this database are available from your local Hewlett-Packard field sales engineer.

For the fifteen million cars and light trucks manufactured each year in North America the manufacturers' savings by using LEDs for the rear exterior signal lights could approach $80 M.

The expected warranty costs depend on a number of factors. The primary factors are bulb voltage and type of driving usage for each vehicle. This analysis assumes a bulb voltage of 12.8 V. Note that an increase in the bulb voltage of 0.2 V causes the bulb failure rates to almost double. The type of driving usage affects the proportion of time that the brake lights, turn signals, and running lights are energized during operation of the vehicle. This analysis assumes a distribution of different driving conditions, roughly 20% of the vehicles doing mostly city driving and the other 80% a mixture of city and highway driving. The bulb mortality curve used in this application note derates the bulb's rated life by a factor of two to account for automotive operating conditions such as DC operation, shock and vibration, operation over temperature, ON/OFF cycles, temperature cycles, and the possibility of moisture inside the signal light. In addition, the bulb mortality curve assumes that there are no infant bulb failures.

Expected Savings of LEDs Over Current Lighting Technologies

	Three year warranty	Four year warranty
Incandescent CHMSL	$3.51	$5.02
Incandescent rear stop/turn/tail (2 units per vehicle)	$2.08	$3.96
Krypton bulb rear stop/turn/tail (2 units per vehicle)	$0.24	$0.92

Because LED lamps have a lifetime several orders of magnitude higher than bulbs, these bulb warranty repair costs can be eliminated. However, it is still important to properly design the LED signal light not to exceed the LED lamp maximum ratings and to use good quality workmanship during the assembly of the printed circuit board. With these precautions, LED signal lights should be expected to last the life of the vehicle.

Warranty Repair Process

During the period that the car is under warranty, the cost of repair is covered by the car manufacturer. This repair process is initiated by the car owner when he returns the vehicle to the dealer for servicing. The car dealer diagnoses the problem and repairs or replaces the defective component. The dealer submits a claim to the car manufacturer. The car manufacturer reimburses the car dealer a fixed rate based on the time and materials needed for the repair. The labor allowance is based on a specified time allowance times a local labor rate. The materials cost is based on the dealer cost plus a specified mark-up (usually 30% to 40%).

The cost to replace a bulb failure in an automotive signal lamp is in the range of \$17 to \$27. This is based on a labor time allowance of 0.2 to 0.3 hours, a local labor rate of \$80/hour (the northern California rate), and a dealer cost of the bulb in the range of \$1 to \$3. The cost may be less in other geographical areas, which may have a lower labor rate.

Bulb Failure Modeling

The probability of failure of an incandescent bulb depends on a number of factors – the rated life of the bulb, the number of hours the bulb is energized, AC/DC operation, the ignition voltage, the operating temperature, the presence of mechanical shock and vibration, and a number of possible bulb quality defects.

In general all bulb manufacturers specify the lifetime of their bulbs in terms of “rated average lab life (hours)”. “Rated average life is that obtained in closely controlled laboratory testing of lamps on 60 Hertz Alternating Current at their design voltage.”[1] Most of the commonly used automotive signaling lamps have a rated average life in the range of 300 to 1200 hours. In many cases, the “rated average life” significantly overstates the average life of a bulb because of environmental stress.

DC operation accelerates the rate of filament “notching”. During normal operation of an incandescent bulb, the surface of the filament develops sawtooth shaped irregularities, which are called “notches”. These notches are caused by preferential evaporation of the tungsten. This notching effect shortens the life of the bulb and also makes the bulb more susceptible to shock and vibration. Notching is especially a problem for very thin filaments. DC operation of the bulb causes the notching to occur more quickly as compared to AC operation. DC operation can reduce the life of incandescent bulbs by over 50%.[2]

Operation of the bulb at voltages higher than the design voltage causes the tungsten in the filament to evaporate at a faster rate. This tungsten is deposited on the glass envelope, which causes it to darken over time. Over time, the filament becomes thinner, which results in an increase in resistance and a reduction in light output. When the only lamp failure mechanism is tungsten evaporation, the expected life of the bulb can be modeled as follows:

$$\text{Life} = \text{Rated Life}\left[\frac{\text{Design Voltage}}{\text{Voltage}}\right]^{n}$$

where:
life = expected lifetime based on operation at applied voltage
rated life = specified life at design voltage
n = exponential acceleration factor

According to bulb manufacturers, n is equal to 12 for small incandescent bulbs.[3]

Operation of the bulb at higher temperatures can induce a number of potential failures. Higher filament temperatures cause the tungsten to evaporate at a faster rate. Based on the work done by Jones and Langmuir, the rate of tungsten evaporation is shown in Figure 1. Note that the evaporation rate varies as a function of filament temperature. At a filament temperature of 2800°K, the rate of evaporation varies as the 33rd power of the filament temperature. Thus a 10°K (or °C) increase in filament temperature reduces the bulb lifetime by 12 per cent.

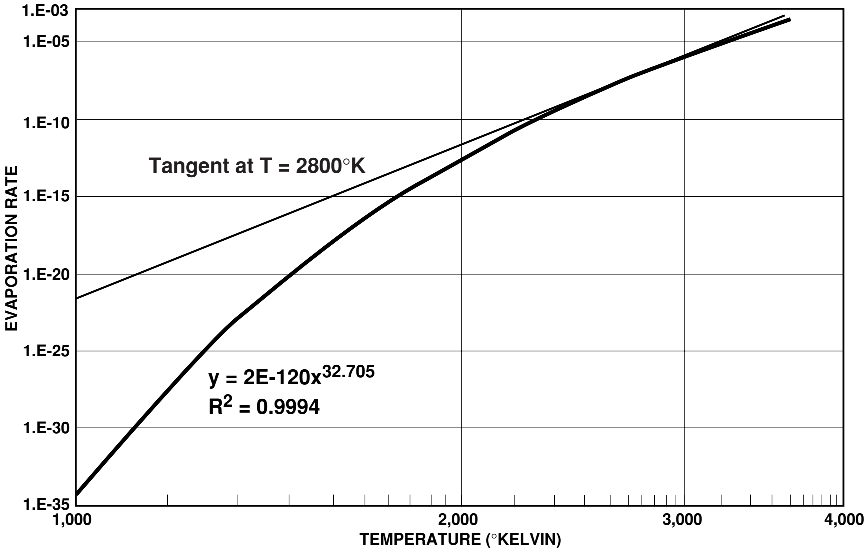

Figure 1. Evaporation of Tungsten (g/cm^2 sec)

In addition, higher temperatures can cause out-gassing of impurities in the glass envelope, glass bead, filament, and support wires. Operation of the glass envelope at temperatures above 100°C can cause the liberation of water vapor inside the bulb and subsequent rapid failure due to the "water cycle."[5] The "water cycle" is a chemical reaction between the oxygen and hydrogen molecules and the tungsten filament which causes tungsten metal to be evaporated from the filament and deposited on the glass envelope. In addition, operation of the glass stem at temperatures close to the softening point of the glass can cause the glass to out-gas, which begins a destructive cycle due to the reduction in vacuum inside the bulb. Since the softening point of soda lime glass is about 370ºC and harder glasses is about 470ºC, this establishes an upper operating temperature limit.[6]

Miniature lamps are susceptible to damage from shock and vibration. The lamp filament is a coiled wire supported at both ends; like a spring, it is free to vibrate. Over time this vibration causes excessive filament twisting, which eventually leads to lamp failure. If a shock imparted to the lamp is great enough, failure will occur immediately.

Shock and vibration analysis and testing of lamps are usually done very early in their operating life. Therefore, the lamps seldom fail. However, as lamps age, filaments become more and more brittle, and consequently, are more vulnerable to shock and vibration failures. Direct current operation will embrittle a filament faster than alternating current, due to the notching previously described. Also, lamps are more prone to fail when no current is being passed through the filament, since the filament is more flexible when cold.[7]

In addition, the number of ON/OFF cycles during which the bulb is energized can adversely effect its lifetime due to the rapid expansion and contraction of the filament. Also, temperature cycling of the glass envelope can lead to premature failure of the bulb.

Due to manufacturing variations from bulb to bulb, the lifetime varies from bulb to bulb. The lamp mortality statistical failure rate can be described by the lamp mortality curve, as shown in Figure 2.[8] Figure 2 shows a typical range of failure rates for "good quality" bulbs. This figure does not show any infant failures due to potential quality defects. Note that 50% of the population of bulbs would be expected to fail prior to the rated life.

The curve shown in Figure 2 is a normal distribution function with a mean (x) equal to 100% rated life and a standard deviation (σ) varying as: $0.20\ x \le \sigma \le 0.25\ x$. Thus, the lamp mortality rate can be written as:

$$R(t) = \int_{-\infty}^{t} \frac{1}{\sqrt{2\pi\sigma}}\, e^{\frac{-(t-\bar{x})^2}{2\sigma^2}}\, dt$$

This equation is also called the normal cumulative distribution function and is given in many statistics handbooks. Also, it is available in most spreadsheet computer programs. For example, in EXCEL, the function can be written as:

$$R(t) = \text{NORMDIST}\ (\ t,\ \bar{x},\ \sigma,\ \text{TRUE}\ )$$

The cumulative effect of these reliability factors (DC operation, shock and vibration, operation over temperature, ON/OFF cycles, temperature cycles, and moisture) can significantly reduce the expected lifetime of a bulb. In addition, there are a number of potential quality defects, which might result in infant failure. As an example, let's consider a #3057 wedge based bulb, which is commonly used in automotive rear combination lamps. The bulb has two filaments. The "tail" filament is rated at 14 V for 5000 hours. The "stop" filament is rated at 12.8 V for 1200 hours. Note that these ratings are for AC operation. The cumulative effect of these other environmental factors might reduce the expected lifetime by 50%, or to 2500 hours and 600 hours, respectively. According to SAE J1211 "Recommended Environmental Practices for Electronic Equipment Design," the nominal ignition voltage is 14.2 V.[9] Allowing for a voltage drop of 1.2 V in the wiring and another 0.2 V drop due to the mechanical switch/connector, gives a bulb voltage of 12.8 V. Note that an increase in the bulb voltage of 0.2 V causes a reduction in the expected lifetime by 16%. However, during the warranty period, a reduction in the expected lifetime causes a much larger change in the value of R(t).

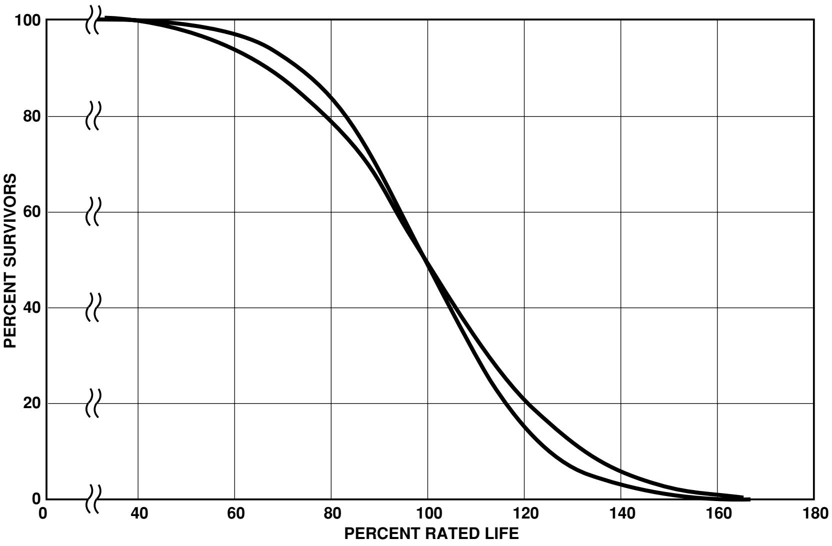

Figure 2. Typical Mortality Curves for a Large Sample of Incandescent Filament Bulbs

Assuming that the #3057 bulb mortality curve is a normal distribution with a mean ($\overline{x}$) equal to the expected derated lifetime and the standard deviation (σ) is equal to 0.225 $\overline{x}$, then the expected life of each filament in the bulb is shown in Figure 3. Note that 0.225 σ is the midpoint in the range shown in Figure 2. This figure assumes a 50% reduction in life between the rated laboratory life and the real-world usage condition.

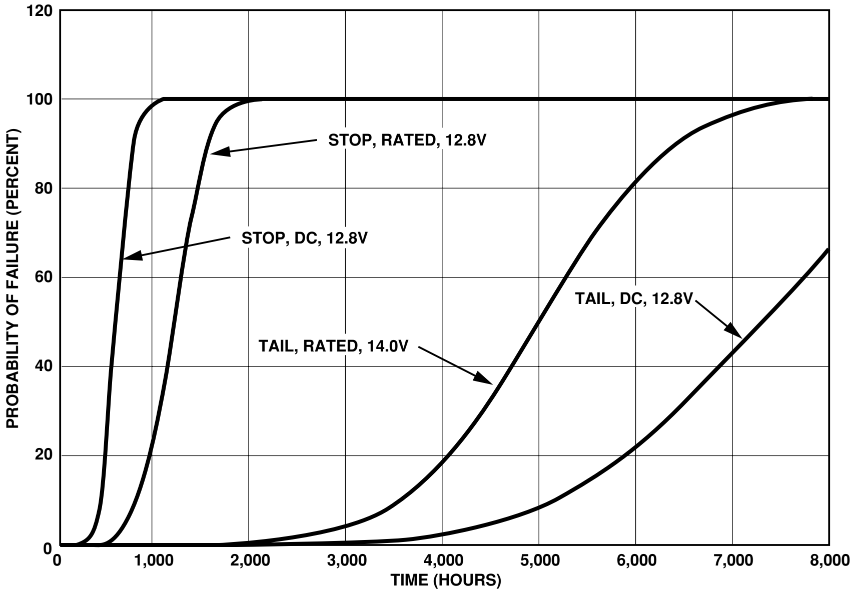

Figure 3. Expected mortality curve for a #3057 bulb with stop and tail filaments operated at 12.8 V dc. Assumes a 50% lifetime reduction to account for dc, typical shock and vibration, and operation over automotive temperature range.

Fleet Utilization Modeling

It is possible to estimate the probability of signal lamp failure during the warranty period. The calculation would need to estimate the number of hours the bulb is energized during the warranty period as well as the expected life of the bulb, based on the factors described above. For the analysis, let's consider both simplified "city" and "suburban highway" situations. The "city" driving scenario assumes that the vehicle is driven at 35 MPH and stopped every 1.5 minutes. The "suburban highway" scenario assumes that the vehicle is driven at 60 MPH and stopped every 9.5 minutes. The detailed assumptions used for these situations are summarized in Appendix B.

Most drivers can be expected to have a mixture of city and highway driving. Table 1 shows the estimated number of hours that each signal lamp will be energized in one year (12,000 miles) of vehicle operation. The values shown in Table 1 are based on the detailed assumptions shown in Appendix B.

Thus the probability of failure of a bulb in a signal light can be estimated by first determining the expected lifetime of the bulb based on the acceleration factors described earlier (DC operation, ignition voltage, temperature, etc). If the bulb has a mortality curve with a normal distribution function such as shown in Figure 2, these acceleration factors might result in curves such as the ones

Table 1. Hours ON per year for the "city" and "suburban highway" driving models

Signal	100% city	80% city	50% city	30% city	20% city	10% city	100% highway
CHMSL	118.4	97.2	65.3	44.1	33.5	22.9	12.3
Stop	118.4	97.2	65.3	44.1	33.5	22.9	12.3
Combined Stop/Turn	113.4	93.0	62.3	41.8	31.6	21.4	11.1
Separate Rear Turn	6.8	5.8	4.4	3.4	2.9	2.4	2.0
Tail/Side	141.9	126.5	103.3	87.8	80.1	72.4	64.7
Front Turn	6.8	5.8	4.4	3.4	2.9	2.4	2.0
Front Side	141.9	126.5	103.3	87.8	80.1	72.4	64.7

in Figure 3. Then the hours of operation of the bulb would be determined, such as shown in Table 1. Using these assumptions, the probability of failure is equal to:

$$R(t) = \text{NORMDIST}\,(\,t\,,\ \bar{x},\ 0.225\,\bar{x},\ \text{TRUE}\,)$$

where: t = filament ON time during the warranty period
$\bar{x}$ = expected bulb lifetime

Dual Filament Bulb Failure Rates

All of the previous calculations estimate a failure rate for a single filament. Many of the bulbs used for automotive signal lighting are dual filament bulbs, such as the #3057 used for the example. In these cases, a bulb failure could be caused by a failure of either filament. Thus, the probability of failure of at least one filament is equal to:

$$P\,(\text{failure} - \text{dual}) = 1 - [\,1 - P\,(\text{fail}_1)]\,[\,1 - P\,(\text{fail}_2)]$$

where:
$P\,(\text{failure} - \text{dual})$ = probability of failure of either filament
$P\,(\text{fail}_1)$ = probability of failure of filament 1
$P\,(\text{fail}_2)$ = probability of failure of filament 2

For example, suppose the probability of failure of each of the filaments is 20% and 5%, then the probability of failure of one or both filaments is equal to 24%:

$$P(\text{failure} - \text{dual}) = 1 - [1 - 0.20]\,[1 - 0.05] = 1\text{-}(0.80)(0.95) = 1\text{-}0.76 = 0.24$$

Multiple Bulb Failure Rates

All of the calculations done previously assume that only a single bulb is used for a given signal light. In many applications, multiple bulbs are used for each signal light function. For example, usually two to four of the same type of bulbs are used for a center-mount stop lamp. In these cases, the probability of a bulb failure is equal to:

$$P(n_k) = \frac{n!}{k!\,(n-k)\,!}\ P\ (\text{failure})^k\ [1 - P\ (\text{failure})\ ]^{(n-k)}$$

where:

$P(n_k)$ = probability of k failures from n bulbs

n = number of identical bulbs driven in parallel
k = number of failures ($0 \leq k \leq n$)
P (failure) = probability of single bulb failure as calculated earlier

For example, suppose four bulbs are used in a center-mount stop lamp and the probability of failure of a single bulb is 10%, then the probability of failure of the bulb(s) in the stop lamp would be calculated as follows:

probability of no failures:	$P(4_0) =$	$(0.9)^4 =$	0.6561 =	65.61%
probability of one failure:	$P(4_1) =$	$4(0.1)(0.9)^3 =$	0.2916 =	29.16%
probability of two failures:	$P(4_2) =$	$6(0.1)^2(0.9)^2 =$	0.0486 =	4.86%
probability of three failures:	$P(4_3) =$	$4(0.1)^3(0.9) =$	0.0036 =	0.36%
probability of four failures:	$P(4_4) =$	$(0.1)^4 =$	0.0001 =	0.01%

Three Year/36,000 Mile Warranty Cost Calculation

Finally, let's apply these mathematical models to estimate the failure rates at the end of a 3 year/ 36,000 mile warranty period for a typical automobile. Table 2 shows a composite automotive design using commonly used bulbs for the various signal lights. The table shows several options for the design of the rear combination lamp.

Table 2 assumptions:

- 3 year / 36,000 miles operation

- Bulb voltage = 12.8 V

- 50% bulb lifetime reduction

- 30% city/ 70% highway driving model

Note that the rated life of the bulbs should be reduced to account for DC operation, ignition voltage, and environmental factors such as elevated temperature, mechanical shock and vibration, filament ON/OFF cycles. The column labeled "filament ON time" was taken from Table 1, with the appropriate values multiplied by three. The column labeled "filament failure rate" is the probability of failure of a single filament in the bulb. The column labeled "signal failure rate" is the composite failure rate. For a multiple bulb signal light, this would correspond to the probability of a failure of one or more bulbs $[1 - P(n_0)]$. For a dual filament bulb, this would correspond to the probability of failure of either filament, P (failure – dual).

As might be expected, the ignition voltage has a significant effect on the bulb failure rates. Increasing the ignition voltage by 0.2 V causes the failure rates to double. Table 3 shows the same example with the ignition voltage increased to 13.0 V.

Table 2. Expected failure rates for automotive signal lights after 3 years of operation with a bulb voltage of 12.8 V. Bulb ON time is based on the 30% city/ 70% highway model.

Signal	Bulb type	Number of bulbs	Rated life (hrs)	Design Voltage	Estimate life (hrs)	Filament on time (hrs)	Filament Failure Rate	Signal Failure Rate
CHMSL	921	2	1000	12.8	500	132.3	**0.0541%**	**0.1082%**
Combined Stop/Turn/ Tail	3057	1	1200	12.8	600	125.5	**0.0220%**	**0.0229%**
			5000	14.0	7328	263.5	**0.0009%**	
Combined Stop/Tail	3057	1	1200	12.8	600	132.3	**0.0266%**	**0.0275%**
			5000	14.0	7328	263.5	**0.0009%**	
Separate Rear Turn	3156	1	1200	12.8	600	10.2	**0.0006%**	**0.0006%**
Rear Side	194	1	2500	14.0	3664	263.5	**0.0019%**	**0.0019%**
Front Park/Turn	3357	1	400	12.8	200	10.2	**0.0012%**	**0.0022%**
	NA		5000	14.0	7328	263.5	**0.0009%**	
Front Side	168	1	1500	14.0	2198	263.5	**0.0046%**	**0.0046%**

Table 3. Expected failure rates for automotive signal lights after 3 years of operation with a bulb voltage of 13.0 V.

Signal	Bulb type	Number of bulbs	Rated life (hrs)	Design Voltage	Estimate life (hrs)	Filament on time (hrs)	Filament Failure Rate	Signal Failure Rate
CHMSL	921	2	1000	12.8	415.1	132.3	**0.1232%**	**0.2463%**
Combined Stop/Turn/ Tail	3057	1	1200	12.8	498.1	125.5	**0.0442%**	**0.0453%**
			5000	14.0	6084	263.5	**0.0011%**	
Combined Stop/Tail	3057	1	1200	12.8	498.1	132.3	**0.0550%**	**0.0560%**
			5000	14.0	6084	263.5	**0.0011%**	
Separate Rear Turn	3156	1	1200	12.8	498.1	10.2	**0.0007%**	**0.0007%**
Rear Side	194	1	2500	14.0	3042	263.5	**0.0025%**	**0.0025%**
Front Park/Turn	3357	1	400	12.8	166.0	10.2	**0.0015%**	**0.0026%**
	NA		5000	14.0	6084	263.5	**0.0011%**	
Front Side	168	1	1500	14.0	1825	263.5	**0.0072%**	**0.0072%**

Since the number of hours that the bulbs are ON during one year of vehicle operation is a function of the driving model (Table 1), then it should not be surprising that the warranty costs are not allocated evenly over the entire population of vehicles. Vehicles with a high percentage of city driving would be expected to have a higher number of bulb failures. Table 4 shows the same example except that the driving model used assumes 50% city/ 50% highway driving, instead of 30% city/ 70% highway driving. Note that for all signal lamps, the failure rates are several times higher than the previous driving model.

Table 4. Expected failure rates for automotive signal lights after 3 years of operation with a bulb voltage of 12.8 V. Bulb ON time is based on the 50% city/ 50% highway model.

Signal	Bulb type	Number of bulbs	Rated life (hrs)	Design Voltage	Estimate life (hrs)	Filament on time (hrs)	Filament Failure Rate	Signal Failure Rate
CHMSL	921	2	1000	12.8	500	196.0	**0.3448%**	**0.6885%**
Combined Stop/Turn/ Tail	3057	1	1200	12.8	600	186.8	**0.1105%**	**0.1115%**
			5000	14.0	7328	309.0	**0.0010%**	
Combined Stop/Tail	3057	1	1200	12.8	600	196.0	**0.1385%**	**0.1395%**
			5000	14.0	7328	309.9	**0.0010%**	
Separate Rear Turn	3156	1	1200	12.8	600	13.2	**0.0007%**	**0.0007%**
Rear Side	194	1	2500	14.0	3664	309.9	**0.0024%**	**0.0024%**
Front Park/Turn	3357	1	400	12.8	200	13.2	**0.0016%**	**0.0027%**
	NA		5000	14.0	7328	309.9	**0.0010%**	
Front Side	168	1	1500	14.0	2198	309.9	**0.0067%**	**0.0067%**

Thus, to arrive at a bulb failure rate for a large population of vehicles, it would be important to estimate the combined driving patterns of the drivers that make up the "fleet". Assuming a distribution of driving patterns shown in Table 5, then it is possible to calculate a "fleet" failure rate for the same hypothetical vehicle shown in Table 2. This "fleet" signal lamp failure rate is shown in Table 6.

Table 5. Assumed "fleet" distribution

Driving Model	Fleet Distribution
100% city	5%
80% city/20% highway	15%
50% city/50% highway	30%
30% city/70% highway	30%
20% city/80% highway	15%
10% city/90% highway	5%
100% highway	0%

Table 6. Expected failure rates for automotive signal lights after 3 years of operation with a bulb voltage of 12.8 V. Failure rates assume the vehicle "fleet" population distribution shown in Table 5.

Signal	Bulb type	Number of bulbs	Rated life (hrs)	Design Voltage	Estimate life (hrs)	Filament Failure Rate	Signal Failure Rate
CHMSL	921	2	1000	12.8	500	**1.10%**	**2.19%**
Combined Stop/Turn/ Tail	3057	1	1200	12.8	600	**0.3074%**	**0.3084%**
			5000	14.0	7328	**0.0010%**	
Combined Stop/Tail	3057	1	1200	12.8	600	**0.3939%**	**0.3949%**
			5000	14.0	7328	**0.0010%**	
Separate Rear Turn	3156	1	1200	12.8	600	**0.0007%**	**0.0007%**
Rear Side	194	1	2500	14.0	3664	**0.0023%**	**0.0023%**
Front Park/Turn	3357	1	400	12.8	200	**0.0016%**	**0.0026%**
	NA		5000	14.0	7328	**0.0010%**	
Front Side	168	1	1500	14.0	2198	**0.0067%**	**0.0067%**

Four Year/50,000 Mile Warranty Cost Calculation

More and more car platforms are converting from a 3 year/ 36,000 mile warranty to a 4 year/ 50,000 mile warranty. Increasing the warranty period from 3 year to 4 years would cause the warranty costs to more than double. This scenario is shown in Table 7. Note that the warranty costs can be expected to increase by a factor of 2 to 8 when the warranty period is increased by one year.

Estimated Warranty Costs For U.S. Cars and Light Trucks

Seventeen 1998 cars and light trucks listed in Appendix A[10] were surveyed to determine the number and types of bulbs used in the signal lamps. Using a similar analysis as shown in Table 6, the average fleet failure costs during the 3 year/36,000 mile warranty period is expected to be $3.51 for CHMSLs, and $1.04 for rear stop/tail and combined stop/turn/tail signal lamps. Thus, each vehicle would be expected to incur these repair costs under warranty assuming that all bulb failures are repaired. For all other signaling functions (rear side markers/tail lamps, rear amber turn signals, front park/turn signals and front side markers), the average fleet failure cost is expected to be less than $0.01.

Note some of the bulbs used for signal lighting are now available with a krypton gas fill. These bulbs are somewhat more expensive but they have twice the rated life of the standard argon gas filled bulbs. Assuming that the dealer cost of krypton bulbs is $0.50 higher (cost plus mark-up, $0.70), the average fleet failure costs during the 3 year/36,000 mile warranty period is expected to be $0.12 for rear stop/tail and combined stop/turn/tail signal lamps.

With the trend towards longer warranty periods, the potential warranty cost savings for LED signal lights becomes even larger. For the seventeen cars and light trucks surveyed, after 4 years/ 50,000 miles, the average fleet failure rates for argon-filled bulbs is expected to be $5.02 for CHMSLs, and $1.98 for rear stop/ tail lamps and combined stop/ turn/tail lamps. For all of the other signaling functions, the average fleet failure costs would be less than $0.01. Using krypton-filled bulbs with a $0.70 assumed dealer cost plus mark-up, after 4 years/50,000 miles, the average fleet failure cost is expected to be $0.46 for rear stop/tail and combined stop/turn/tail signal lamps.

Table 7. Expected failure rates for automotive signal lights after 4 years (50,000 miles) of operation with a bulb voltage of 12.8 V. Failure rates assume the vehicle "fleet" population distribution shown in Table 5.

Signal	Bulb type	Number of bulbs	Rated life (hrs)	Design Voltage	Estimate life (hrs)	Filament Failure Rate	Signal Failure Rate
CHMSL	921	2	1000	12.8	500	**6.10%**	**11.8%**
Combined Stop/Turn/ Tail	3057	1	1200	12.8	600	**1.93%**	**1.93%**
			5000	14.0	7328	**0.0014%**	
Combined Stop/Tail	3057	1	1200	12.8	600	**2.46%**	**2.46%**
			5000	14.0	7328	**0.0014%**	
Separate Rear Turn	3156	1	1200	12.8	600	**0.0008%**	**0.0008%**
Rear Side	194	1	2500	14.0	3664	**0.0043%**	**0.0043%**
Front Park/Turn	3357	1	400	12.8	200	**0.0027%**	**0.0041%**
	NA		5000	14.0	7328	**0.0014%**	
Front Side	168	1	1500	14.0	2198	**0.0183%**	**0.0183%**

Conclusion

Because LED lamps have a lifetime several orders of magnitude higher than bulbs, these bulb warranty repair costs can be significantly reduced. Properly designed, an LED automotive signal light should operate reliably for the life of the vehicle. However, it is still important to design the LED signal light such as not to exceed the maximum drive current and junction temperature of the LED lamps. Furthermore, it is important to use good quality workmanship during the assembly of the printed circuit board. For complete details on the design of LED automotive signal lights, please see Hewlett-Packard Application Note 1149.

Appendix A

MY98 cars used in survey [10]

Car	Tail/Turn/ Brake	Tail/Brake	Amber Rear Turn	Rear Tail	CHMSL	Rear Side Marker	Front Park/Turn	Front Side Marker
Buick LeSabre	3357	—	—	194 x 2	1156 x 2	194	3357	194
Chevrolet Cavalier	3057	—	—	—	912 x 2	194	3357	194
Dodge Intrepid	—	3157 x 2	3157	—	912 x 2	168	3157NA	—
Dodge Neon	3157	—	—	—	921	916	3157NA	168
Dodge Stratus	—	3057	3057	—	921	3057	3157NA	—
Ford Contour	1157	—	—	—	2723 x 9	—	2357NA	—
Ford Escort	3157 x 2	—	—	—	921	168	3457NA x 2	194
Pontiac Grand Am	—	3357 x 2	3357	—	912 x 2	194	3357NA	—
Saturn SC2	—	2057 x 2	1156	—	921 x 3	—	3357NA	168
Saturn SL2	—	2057	1156	—	PC175 x 6	194	3357NA	168

MY98 trucks used in survey [10]

Car	Tail/Turn/ Brake	Tail/Brake	Amber Rear Turn	Rear Tail	CHMSL	Rear Side Marker	Front Park/Turn	Front Side Marker
Chevrolet S-10	3057	—	—	3057	211-2 x 2	—	3157NA	194
Chevrolet Tahoe	3057	—	—	3057	LED	—	2357NA x 2	194
Dodge Gr Caravan	—	3057	3057 (Turn/Tail)	—	921 x 3	—	3157NA	—
Dodge Ram 1500	3157	—	—	—	921 x 2	194	3157NA	—
Ford Explorer	—	3157	3156	—	LED	—	3157NA x 2	916NA
Ford F150	3157	—	—	3157	912	—	3157NA	916NA
Jeep Grand Cherokee	—	3057	3057	—	922 x 3	194	1295NA x 2	194NA

Bulbs used in survey [11], [12], [13]

Lamp	Size	Base	Fill Gas	Design Voltage	Design Current	Design mscd	Rated Life
168	T - 3¼	Wedge	Vacuum	14.0	0.35	3.0	1500
PC175	T - 3¼	PCB		14.0	0.58	5.0	1000
194	T - 3¼	Wedge	Vacuum	14.0	0.27	2.0	2500
194NA	T - 3¼	Wedge	Vacuum	14.0	0.27	1.5	2500
211-2	T-3	Double end cap	Gas	12.8	0.97	12.0	1000
912	T-5	Wedge	Gas	12.8	1.00	12.0	1000
916	T-5	Wedge	Gas	13.5	0.54	2.0	10,000
916NA	T-5	Wedge	Gas	13.5	0.54	1.5	10,000
921	T-5	Wedge	Gas	12.8	1.40	21.0	1000
922	T-5	Wedge	Gas	12.8	0.98	15.0	200
1156	S - 8	SC Bayonet	Gas	12.8	2.10	32.0	1200
1157	S - 8	DC Index	Gas	12.8	2.10	32.0	1200
				14.0	0.59	3.0	5000
1295NA	S - 8	SC Bayonet	Gas	12.5	3.00	37.0	200
2057	S - 8	DC Index	Gas	12.8	2.10	32.0	1200
				14.0	0.49	2.0	5000
2357NA	S - 8	DC Index	Gas	12.8	2.23	30.0	400
				14.0	0.59	2.25	5000
2723	T - 1¾	W2 x 4.6d		12.0	0.20	1.5	1100
3057	GT - 8	DC Wedge	Gas	12.8	2.10	32.0	1200
				14.0	0.48	2.0	5000
3156	GT - 8	SC Wedge	Gas	12.8	2.10	32.0	1200
3157	GT - 8	DC Wedge	Gas	12.8	2.10	32.0	1200
				14.0	0.59	3.0	5000
3157NA	GT - 8	DC Wedge	Gas	12.8	2.10	24.0	1200
				14.0	0.59	2.2	5000
3357	GT-8	DC Wedge	Gas	12.8	2.23	40.0	400
				14.0	0.59	3.0	5000
3357NA	GT - 8	DC Wedge	Gas	12.8	2.23	30.0	400
				14.0	0.59	2.2	5000
3457NA	GT - 8	DC Wedge	Gas	12.8	2.23	30.0	400
				14.0	0.59	2.2	5000

Appendix B

Assumptions:

1 year car life = 12,000 miles
scale times shown by 36K/12K or 50K/12K ratios for two warranty cases

City driving case:

Car is either moving at 35 mph, stopped, or constant acceleration/deceleration

Stop profile:

- constant speed for 1.5 min, decelerate, stop for 0.5 min, accelerate to original speed
- takes 10 sec to accelerate from 0 to 35 mph (5.1 ft/sec^2)
- takes 3.4 sec to decelerate from 35 mph to 0 (15 ft/sec^2)
- brake is depressed while car is stopped

Turn profile:

- 50% flashing ON/OFF duty cycle
- 20% of stop/go brake cycles are turn cycles
- signal turns 5 sec prior to braking
- turn signal energized while stopped

Tail profile:

- 30% time car is driven at night with tail on

Then, one year (12,000 miles) is equal to:

- ignition time = 473.08 hrs
- 118.45 hrs “brake depressed” separate brake signal
- 113.41 hrs “brake depressed” combined brake/turn signal
- 27.2 hrs “turn signal flashing” (6.81 hrs each turn bulb energized)
- 141.92 hrs “tail on”
- each year has 12,758.29 stop/go brake cycles
- each year has 1,275.83 left or right turn signal cycles

For the “city” driving model, the vehicle is being driven for 1.5 minutes at 35 MPH (with a distance traveled of 0.88 miles). Then the car is stopped for 0.5 minutes. Afterwards, the vehicle is accelerated back to 35 MPH. This cycle would be repeated over and over. Note that in one year of driving, the vehicle would be subjected to 12,758 braking/acceleration cycles. Further, let’s assume that for 20% of the braking/acceleration cycles, that either the left or right turn signal is energized. In one year, the vehicle would be driven for 473 hours. Also, in one year, the “stop” filament would be energized for 118 hours and the “tail” filament would be energized for 142 hours. Assuming that the turn signal uses a different bulb than the stop signal, than each “turn” filament would be energized for 6.8 hours.

Suburban Highway driving case:

Car is either moving at 60 mph, stopped, or constant acceleration/ deceleration

Stop profile:

- Constant speed for 9.5 min, decelerate, stop for 0.5 min, accelerate to original speed
- Takes 25 sec to accelerate from 0 to 60 mph (3.5 ft/sec^2)
- Takes 5.9 sec to decelerate from 60 mph to 0 (15 ft/sec^2)
- Brake is depressed while car is stopped

Turn profile:

- 50% flashing ON/OFF duty cycle
- 50% of stop/go brake cycles are turn cycles
- Signal turns 10 sec prior to braking
- Turn signal energized while stopped

Tail profile:

- 30% time car is driven at night with tail on

Then, one year (12,000 miles) is equal to:

- Ignition time = 215.54 hrs
- 12.25 hrs “brake depressed” separate brake signal
- 11.15 hrs “brake depressed” combined brake/turn signal
- 7.8 hrs “turn signal flashing” (1.96 hrs each turn bulb energized)
- 64.66 hrs “tail on”
- each year has 1229.71 stop/go brake cycles
- each year has 307.43 left or right turn signal cycles

For the “suburban highway” driving model, the vehicle is being driven for 9.5 minutes at 60 MPH (with a distance traveled of 9.5 miles). Then the car is stopped for 0.5 minutes. Afterwards, the vehicle is accelerated back to 60 MPH. This cycle would be repeated over and over. Note, that in one year of driving, the vehicle would be subjected to 1,230 braking/acceleration cycles. Further, let’s assume that for 50% of the braking/acceleration cycles, that either the left or right turn signal is energized. In one year, the vehicle would be driven for 216 hours. Also, in one year, the “stop” filament would be energized for 12.3 hours and the “tail” filament would be energized for 64.7 hours. Assuming that the turn signal uses a different bulb than the stop signal, than each “turn” filament would be energized for 2.0 hours.

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12. Wagner *Lighting*, *Lamp and Flasher Specification Supplement A21S*, (Chesterfield, MO: Cooper Industries, 1997)

13. GE Lighting, (used for fill-gas column)

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