Lower Bound on Reliability for Weibull Distribution When Shape Parameter is not Estimated Accurately

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SUMMARY AND CONCLUSION

This paper investigates the mathematical relationships between the shape parameter $\beta$ and estimates of reliability and a life limit lower bound for the two parameter Weibull distribution. It shows that under rather general conditions, both the reliability lower bound and the allowable life limit lower bound (often called a tolerance limit) have unique global minimums over a range of $\beta$. Hence lower bound solutions can be obtained without assuming or estimating $\beta$. The existence and uniqueness of these lower bounds are proven in the Appendix. Some real data examples are given to show how these lower bounds can be easily established and to demonstrate their practicality. The method developed in the paper has proven to be extremely useful when using the Weibull distribution in analysis of no-failure or few-failures data. The results are applicable not only in the aerospace industry but anywhere that system reliabilities are high.

INTRODUCTION

The two parameter Weibull distribution is widely used for reliability and life limit estimations. However, there is often
insufficient information, e.g., failure data, to accurately estimate the shape parameter $\beta$ of the distribution. Traditionally, either a value of $\beta$ is assumed and then used to establish the scale parameter $\alpha$ and estimate a reliability lower bound, or a nonparametric method is invoked to estimate a reliability lower bound. In the former situation the assumption of $\beta$ is often controversial and difficult to justify. In the latter case, the reliability bound estimated is usually too conservative. This paper presents an alternate method which attempts to overcome the drawbacks in the traditional methods.

**NOTATION AND ASSUMPTION**

Notation:

- **Cdf**: Cumulative distribution function
- **$\beta$**: Weibull distribution shape parameter (slope value)
- **$\alpha$**: Weibull distribution scale parameter (characteristic value)
- **$\hat{p}$**: Estimate of any parameter, $p$
- **$n$**: Total number of test units
- **$r$**: Number of failed units
- **$t_i$**: Operating time (seconds, cycles)
- **$t_m$**: $\max(t_1,t_2,\ldots,t_n)$
- **$z_i$**: $t_i/t_m$, normalized time
- **$T$**: Specific operating time or life limit lower bound
- **$R$**: Reliability for a given life limit
- **$T_c$**: Conditional life limit lower bound
- **$R_c$**: Conditional reliability
MTBF  Mean time between failure
τ  Confidence level
In  Natural logarithm

Assumption:

For the hardware units, the distribution of operating time to failure is the 2-parameter Weibull.

**MATHEMATICAL RESULTS**

The 2-parameter Weibull Cdf is:

\[ F(t) = 1 - \exp\left( -\frac{t}{\alpha} \right)^\beta, \quad t>0 \]  

(1)

Where \( t \) is a variable generally given in terms of time or cycles, \( \beta \) is the shape or slope parameter of the distribution and \( \alpha \) is the scale or characteristic life parameter. Assume \( n \) units are tested. Let \( t_1, t_2, \ldots, t_r \) be failure data and \( t_{r+1}, t_{r+2}, \ldots, t_n \) be censored data (either failure censoring or time censoring).

A lower bound on \( \alpha \) results from the fact that if \( t \) is distributed as Weibull \((\beta, \alpha)\) then \( t^\beta \) has an exponential distribution with MTBF parameter \( \alpha^\beta \). Thus given a value of \( \beta \), a 100\( \tau \) percent confidence lower bound on \( \alpha \) (Refs. 1 - 4) is given by:

\[ \hat{\alpha} = \left( \frac{\sum t_i^\beta}{c(\tau)} \right)^{1/\beta}, \]  

(2)

where \( c(\tau) \) is a positive constant which depends on the confidence level \( \tau \), the number of failures \( r \) and the censoring scheme. For example, for type II censoring, \( c(\tau) = 0.5X^\tau r, 2r \); for type I censoring with replacement, \( c(\tau) = 0.5X^\tau r, 2r+2 \) (Ref. 4), where \( X^\tau r,k \) is the 100\( \tau \) percentile of the Chi-square distribution with degrees of freedom \( k \).
With high reliability systems a value of \( \beta \) is frequently hard to come by. Either there are no failures in which case \( \beta \) cannot be estimated or there are few failures in which case the estimate of \( \beta \) is subject to considerable uncertainty, and no assumption about \( \beta \) based on similar failure modes or similar hardware is available. Fortunately, it turns out that under certain conditions, which are not so restrictive, reliability for a given life or life limit for a given reliability experiences a minimum value as a function of \( \beta \). In other words there is a "worst case \( \beta \)", say \( \beta_0 \), such that reliability or life limit attains a strict minimum when \( \beta = \beta_0 \). The equations and conditions are shown below.

Reliability lower bound:

When the unit is tested to time \( T \), it is easily seen that the 100\% confidence lower bound on reliability is

\[
\hat{R} = R(\beta) = \exp\left(-\frac{T^\beta}{\hat{\delta}^\beta}\right) = \exp\left(-c(r)\frac{T^\beta}{\sum t_i^\beta}\right)
\]  

(3)

Theorem 1: Under the condition: \( (t_1 t_2 \ldots t_n)^{1/n} < T < \max(t_1, t_2, \ldots, t_n) \), there exists a unique \( \beta_0 > 0 \) such that\[
\hat{R}(\beta) > \hat{R}(\beta_0), \text{ for all } \beta > 0 \text{ and } \beta \neq \beta_0;
\] and \( \hat{R}(\beta) \) is a monotone increasing function of \( \beta \) when \( \beta \geq \beta_0 \), and \( \hat{R}(\beta) \) is a monotone decreasing function of \( \beta \) when \( \beta \leq \beta_0 \).

For all theorems presented here, when the conditions are not met, the function in question is either monotonically increasing or monotonically decreasing over the range of \( \beta \), in either case a worst case \( \beta \) does not exist.

Allowable life limit lower bound:

Assuming the reliability is a given constant \( R \), we solve for \( T \)
from (3), then a 100\% percent confidence lower bound on allowable life limit (tolerance limit) is

\[
\hat{T} = \hat{T}(\beta) = \left( - \ln(R) \frac{\sum t_i^\beta}{c(\tau)} \right)^{1/\beta}
\]  

(4)

**Theorem 2:** Under the condition: \( k < \frac{c(\tau)}{-\ln(R)} < n \), where \( k \) = number of \( t_i \)'s with values = \( \max(t_1, t_2, \ldots, t_n) \), there exists a unique \( \beta_0 > 0 \) such that:

\[
\hat{T}(\beta) > \hat{T}(\beta_0), \text{ for all } \beta > 0 \text{ and } \beta \neq \beta_0;
\]

and \( \hat{T}(\beta) \) is a monotone increasing function of \( \beta \) when \( \beta \geq \beta_0 \),

and \( \hat{T}(\beta) \) is a monotone decreasing function of \( \beta \) when \( \beta \leq \beta_0 \).

Rocket engine reliability is more commonly thought of in terms of mission reliability rather than life time reliability. Thus there is interest in the reliability of the next \( t_0 \) second mission given that the unit has already accumulated \( T-t_0 \) seconds. The equations and conditions for the conditional reliability and life limit are given below.

**Conditional reliability lower bound:**

We define the conditional reliability \( R_C \) as the probability that the unit will not fail during the next \( t_0 \) seconds, given that the unit has survived the first \( T-t_0 \) seconds. Then \( R_C \) is computed by

\[
R_C = \exp\left( - \frac{T^\beta - (T-t_0)^\beta}{\alpha^\beta} \right).
\]

(5)

Substituting equation (2) into equation (5), we get the 100\% percent confidence lower bound on \( R_C \):

\[
\hat{R}_C = \hat{R}_C(\beta) = \exp\left( - \frac{c(\tau) T^\beta - (T-t_0)^\beta}{\sum t_i^\beta} \right)
\]

(6)

**Theorem 3:** Under the conditions: \( 0 < t_0 < T < \max(t_1, t_2, \ldots, t_n) \)

and \( \sum t_i(1+\ln(T/t_i)) < 0 \) there exists a \( \beta_0 > 1 \) such that
\[ R_c(\beta) \geq \exp(-c(\tau) \frac{t_0 \beta_0 \beta_0^{-1}}{\Sigma t_i \beta_0}), \text{ for all } \beta > 1. \] (7)

**Conditional operating life limit lower bound:**

We frequently need to assess a lower bound for a conditional operating life limit \( T_c \) which is defined by (5) for a given conditional reliability \( R_c \). While \( T_c \) cannot be explicitly solved for from (5), it can be treated as an implicit function of other variables.

**Theorem 4.** Under the conditions:

\[ R_c < \exp(-c(\tau) \frac{t_0}{\Sigma t_i}) \text{ and } \Sigma t_i \ln(\frac{t_i}{t_0}) > 0, \] (8)

there exists a \( \beta_0 > 1 \) such that

\[ \hat{T}_c(\beta) \geq \left( -\ln(R_c) \frac{\Sigma t_i \beta_0}{c(\tau) \beta_0 t_0} \right)^{1/(\beta_0-1)}, \text{ for all } \beta > 1. \] (9)

Note that Theorems 3 and 4 have been restricted to \( \beta > 1 \) (wearout type failures). Similar work for \( \beta \leq 1 \) (infant mortality type failures and constant failure rate type failures) will be the subject of a future paper.

The proofs of the Theorems 1 to 4 are given in the Appendix and a computer program has been written to solve for the \( \beta_0 \)'s and the minimums.

**ILLUSTRATIVE EXAMPLES**

Example 1. Of the 59 units of a particular component that were tested only one failed. The operating times (seconds) of the 59 units are: 14176 (failure), 28587, 20359, 18248, 17256, 16769, 13890, 13357 13118, 13118, 13061, 12893, 12640, 11878, 11858, 10378, 8172, 7918, 7379, 7326, 6700, 6442, 6263, 6168, 5809, 5383, 5305, 4788, 4788, 4784, 4748, 4701, 4453, 4258, 3696, 3145, 3138,
We wish to use the Weibull distribution to assess the reliability lower bound at the 50% confidence level for a new unit operated for 10,000 seconds.

Since we have just one failure, we are not able to obtain a good estimate of $\beta$. Using Theorem 1 with:

$$\tau = .50; \ c(\tau) = X^\tau,4=3.357 \text{ and } T = 10,000 \text{ seconds,}$$

we have

$$R(\beta) = \exp(-.5*3.357 \frac{10000^\beta}{\sum t_i^\beta})$$

From Theorem 1, we know there exists a unique $\beta_0 > 0$ (Figure 1) such that

$$R(\beta) \geq R(\beta_0) \text{ for all } \beta_0 > 0.$$  

The computer program computes: $\beta_0 = 1.083$ and $R(\beta_0) = .958$. Therefore we may conclude with 50% confidence that the reliability of a unit operated for 10,000 seconds is at least .958.

Example 2. Sixteen units of a particular component experienced the following cycles with no failure: 35, 31, 26, 21, 40, 30, 38, 27, 23, 38, 18, 19, 12, 14, 13, 9. Given these data, what is the minimum number of tests which can be run without failure at .95 reliability and 50% confidence level?

We have: $R=.95$, $\tau=.50$ and $c(\tau)=.5*X^\tau,2=1.386$. Using Theorem 2 (see Figure 2), we get:

$$\beta_0 = 1.529 \text{ and } T(\beta_0) = 28.6 \text{ starts}$$

So we conclude that at the 50% confidence level and 0.95 reliability, the component could be tested for at least 28 cycles without failure.
Example 3. Using the data in Example 1 compute the 90% confidence lower bound on reliability for 520 seconds of operation given that the unit had already operated for 5000 seconds without failing.

We have $T=5000+520=5520$ seconds, $t_0=520$ seconds, $r=.90$ and $c(r)=.5*X^2_{\tau,4}=7.779$. Using Theorem 3 (see Figure 3), we get:

$$\beta_0 = 1.321$$

and equation (7) gives

$$R_c(\beta) \geq \exp\left(-.5*7.779{520*1.321*5520}^{1.321-1}\right) = .9945, \text{ for all } \beta > 1.$$

Thus we conclude, with 90% confidence, that the conditional reliability of a unit operating for 520 seconds given that it had already operated for 5000 seconds is at least .9945.

Example 4. Again using Example 1 data compute the life limit such that a 520 second operation reliability of at least .99 is guaranteed at the 95% confidence level.

We have $t_0=520$ seconds, $r=.95$, $c(r)=.5*X^2_{\tau,4}=9.488$ and $R_c=.99$. Using Theorem 4 (see Figure 4), we get:

$$\beta_0 = 2.188$$

and equation (9) gives

$$T_c(\beta) \geq (-\ln(.99)\frac{\Sigma t_{i 2.188}}{.5*9.488*2.188*520})^{1/(2.188-1)}$$

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=9,486 seconds, for all $\beta > 1$.

So we see, in order to meet 0.99 reliability lower bound at 95% confidence level, the conditional life limit is at least 9,486 seconds.

APPENDIX

1. Proof of Theorem 1:

From (3), we get: 
\[ \hat{R}(\beta) = \exp\left(-c(\tau)\frac{T^\beta}{\sum t_i^\beta}\right) \]

It is obvious that finding a minimum for $\hat{R}(\beta)$ is equivalent to finding a minimum for $g(\beta) = \sum (t_i/T)^\beta$.

The first derivative and the second derivative of $g(\beta)$ are 
\[ g'(\beta) = \sum \ln\left(\frac{t_i}{T}\right) \times (\frac{t_i}{T})^\beta \]
and 
\[ g''(\beta) = \sum (\ln\left(\frac{t_i}{T}\right))^2 \times (\frac{t_i}{T})^\beta \]

From (1.2), and the given condition:
\[ (t_1t_2...t_n)^{1/n} < T < \max(t_1,t_2,...,t_n) \]
we see $g''(\beta) > 0$. So $g'(\beta)$ is a strictly monotone increasing function of $\beta$. Also because of (1.3), we have
\[ \lim_{\beta \to 0} g'(\beta) = \sum \ln (\frac{t_i}{T}) = \ln \left( \frac{t_1}{T} \frac{t_2}{T} \cdots \frac{t_n}{T} \right) < 0 \]

and \( \lim_{\beta \to +\infty} g'(\beta) = +\infty > 0 \). Therefore there exists a unique \( \beta_0 > 0 \) such that:

- \( g'(\beta_0) = 0 \) and \( g(\beta) \) attains a minimum at \( \beta_0 \);
- \( g(\beta) \) is a monotone increasing function of \( \beta \) when \( \beta \geq \beta_0 \),
- \( g(\beta) \) is a monotone decreasing function of \( \beta \) when \( \beta \leq \beta_0 \).

Transferring the result from \( g(\beta) \) back to \( R(\beta) \), we conclude the Theorem 1.

2. Proof of Theorem 2:

From (4) we get
\[ \hat{T}(\beta) = (\frac{\sum t_i \beta}{C(\tau)})^{1/\beta} \]

Using the notations \( t_m = \max(t_1, t_2, \ldots, t_n) \), \( z_i = t_i / t_m \), \( i = 1, 2, \ldots n \); and \( C = -\ln R / c(\tau) \). We have
\[ \frac{\hat{T}(\beta)}{t_m} = (C \Sigma z_i \beta)^{1/\beta} = \exp \left( \frac{\ln(C) + \ln(\Sigma z_i \beta)}{\beta} \right) \]  

(2.1)

Define \( h(\beta) = (\frac{\ln(C) + \ln(\Sigma z_i \beta)}{\beta}) \). We have \( \frac{\hat{T}(\beta)}{t_m} = \exp(h(\beta)) \).

The first derivative of \( h(\beta) \) is
\[ h'(\beta) = (\frac{-\ln C + \beta \ln z_i z_i \beta}{\Sigma z_i \beta}) / \beta^2 \]

Defining \( h_1(\beta) = -\ln C + \beta \frac{\sum_{i} \ln(z_i) z_i \beta}{\Sigma z_i \beta} - \ln(\Sigma z_i \beta) \),
(2.2)

we have \( h'(\beta) = h_1(\beta) / \beta^2 \). The first derivative of \( h_1(\beta) \) is
\[
h_1'(\beta) = \frac{\sum_{i} \ln(z_i) z_i \beta}{\Sigma z_i \beta} + \beta \frac{(\sum_{i} \ln(z_i) z_i \beta)(\Sigma z_i \beta) - (\ln(z_i) z_i \beta)^2}{(\Sigma z_i \beta)^2} - \frac{\sum_{i} \ln(z_i) z_i \beta}{\Sigma z_i \beta}
= \beta \frac{(\sum_{i} \ln(z_i) z_i \beta)(\Sigma z_i \beta) - (\sum \ln(z_i) z_i \beta)^2}{(\Sigma z_i \beta)^2} \]  

Using the Cauchy Inequality (Ref. 6, Page I1), we have \( h_1'(\beta) \geq 0 \).

But by the given condition \( k < c(\tau) / (-\ln R) < n \), where \( k = \) number of
t_i's with values=tm, the equality does not hold. So
h_1'(β)>0. Hence h_1(β) is a strictly monotone increasing
function of β.

Using the condition k<μ(γ)/(-Ln(R))<n again, we have

\[ \lim_{β \to 0} h_1(β) = -\ln C + 0 - \ln n = -\ln (Cn) < 0 \]
and

\[ \lim_{β \to \infty} h_1(β) = -\ln C + 0 - \ln k = -\ln (Ck) > 0. \]

Therefore, there exists a unique β_0>0 such that h_1(β_0)=0,
and \( h_1(β)<0 \) when \( β≤β_0 \),
and \( h_1(β)>0 \) when \( β≥β_0 \).

Noticing \( h_1(β)=h'(β)β^2 \), we can conclude there exists a unique
β_0>0 such that \( h'(β_0)=0 \) and \( h(β) \) attains a minimum at β_0;
and \( h(β) \) is a monotone increasing function of β when \( β≥β_0 \),
and \( h(β) \) is a monotone decreasing function of β when \( β≤β_0 \).

Transferring the result from \( h(β) \) back to \( T(β) \), we conclude
the Theorem 2.

3. Proof of Theorem 3:

From (6), we have

\[ R_c(β) = \exp(-c(γ)\frac{T^β-(T-t_0)^β}{Σ^β}) \]

Using the notations defined in the Notation Section, we have

\[ \frac{-\ln R_c(β)}{c(γ)} = \frac{(T/t_m)^β-(T-t_0)/(tm)^β}{Σ^β_i} \]

(3.1)

Using the first order Taylor expansion, R.H.S. (right hand side)
of (3.1) = \[ \frac{β(t_0/t_m)((T-t_0)/(tm))^β}{Σ^β_i} \]

where 0≤θ≤1

Considering \( β>1 \), we get

\[ \frac{-\ln R_c(β)}{c(γ)} ≤ \frac{β(t_0/t_m)(T/t_m)^β}{Σ^β_i} = z(β) \]

(3.2)
Define \( z_1(β) = \ln (z(β)t_m/t_0) = \ln β+(β-1)\ln (T/t_m)-\ln (Σ^β_i) \).

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The first derivative and the second derivative of $z_1(\beta)$ are

$$z_1'(\beta) = \frac{1}{\beta} + \ln\left(\frac{T}{t_m}\right) - \frac{\sum \beta \ln z_i}{\sum z_i}$$

and

$$z_1''(\beta) = -\frac{1}{\beta^2} - \frac{(\sum \beta (\ln z_i)^2)(\sum \beta^2) - (\sum \beta \ln z_i)^2}{(\sum z_i)^2} \tag{3.4}$$

By the Cauchy Inequality, the second term of R.H.S. of (3.4) ≤ 0.

So $z_1''(\beta) < 0$. Therefore $z_1'(\beta)$ is a strictly monotone decreasing function of $\beta$. Because of the given conditions, we also have

$$\lim_{\beta \to +\infty} z_1'(\beta) = 1 + \ln\left(\frac{T}{t_m}\right) - \frac{\sum \beta \ln z_i}{\sum z_i} > 0$$

and

$$\lim_{\beta \to +\infty} z_1'(\beta) = 0 + \ln(T/t_m) - 0 < 0.$$

So there exists a unique $\beta_0 > 0$ such that $z_1'(\beta) = 0$ and $z_1(\beta)$ attains a maximum at $\beta_0$. But noticing

$$z(\beta) = (t_0/t_m) \exp(z_1(\beta)),$$

we could extend the result to $z(\beta)$. So we have

$$\frac{-\ln(R_C(\beta))}{C(\tau)} \leq \frac{\beta_0 t_0 \tau^{\beta_0 - 1}}{\sum \beta} = z(\beta) \leq z(\beta_0) = \frac{\beta_0 t_0 \tau^{\beta_0 - 1}}{\sum \beta}, \quad \text{for all } \beta > 1.$$

That is, $R_C(\beta) \geq \exp\left(-C(\tau)\frac{\beta_0 t_0 \tau^{\beta_0 - 1}}{\sum \beta}\right)$, for all $\beta > 1$.

4. Proof of Theorem 4:

From (6), we have

$$\frac{-\ln R_C}{C(\tau)} = \frac{T_c - (T_c - t_0)\beta}{\sum \beta} = \frac{(T_c/t_m)\beta - (T_c - t_0)/t_m}{\sum \beta} \tag{4.1}$$

First, we have to show, for any $R_C$, $C(\tau)$, $t_0$, $\beta$, $t_i$'s and under the given conditions (8), a unique $T_c = T_c(\beta)$ can be solved for from (4.1).

Define $f(T_c) = T_c^\beta - (T_c - t_0)^\beta - \sum \beta \left(-\frac{\ln R_C}{C(\tau)}\right)$.

Taking the derivative with respect to $T_c$, we have
\[ f'(T_c) = \beta T_c^{\beta-1} - \beta (T_c - t_0)^{\beta-1} > 0. \]

We also have \[ T_c \lim_{T_c \to T_0} f(T_c) = +\infty > 0 \]

\[ \lim_{T_c \to T_0} f(T_c) = t_0^\beta - \sum_{i} \beta \left( \frac{-\ln R_c}{c(\tau)} \right) < 0, \text{ because of (8).} \]

Therefore, a unique solution \( T_c = T_c(\beta) \) exists for the equation (4.1).

Using a Taylor expansion, we have

\[ \frac{-\ln R_c}{c(\tau)} = \beta(t_0/tm)((T_c - t_0)/tm)^{\beta-1}, \text{ where } 0 \leq \theta \leq 1 \]  

(4.2)

Solving for \( T_c(\beta) \) from (4.2), we have

\[ \frac{T_c(\beta)}{t_m} = \left( \frac{-\ln R_c}{c(\tau)} \frac{\sum_i \beta}{t_0} \right)^{1/(\beta-1)} + \frac{t_0}{t_m} \]  

\[ \geq \left( \frac{-\ln R_c}{c(\tau)} \frac{\sum_i \beta}{t_0} \right)^{1/(\beta-1)} = w(\beta) \]  

Let \( W = t_m(-\ln R_c/c(\tau))/t_0 \), (constant, independent of \( \beta \)) and

\[ w_1(\beta) = \ln w(\beta) = \frac{\ln W + \ln(\sum_i \beta) - \ln \beta}{\beta-1}. \]

The first derivative of \( w_1(\beta) \) is

\[ w_1'(\beta) = \frac{-\ln W}{(\beta-1)^2} + \frac{\sum_i \beta \ln z_i (\beta-1) - \ln(\sum_i \beta)}{(\beta-1)^2} - \frac{(\beta-1)/\beta - \ln \beta}{(\beta-1)^2} \]  

\[ = -1 + 1/\beta - \ln W + \ln \beta + \frac{\sum_i \beta \ln z_i (\beta-1) - \ln(\sum_i \beta)}{(\beta-1)^2} \]  

(4.3)

Let the numerator of R.H.S of (4.3) = \( w_2(\beta) \). Then

\[ w_2'(\beta) = \frac{\beta-1}{\beta^2} + \frac{\sum_i \beta \ln z_i}{\sum_i \beta} + (\beta-1)(\frac{\sum_i \beta (\ln z_i)^2}{(\sum_i \beta)^2} - (\sum_i \beta (\ln z_i)^2)}{(\sum_i \beta)^2} \]

\[ = \frac{\beta-1}{\beta^2} + (\beta-1)(\frac{\sum_i \beta (\ln z_i)^2}{(\sum_i \beta)^2} - (\sum_i \beta (\ln z_i)^2)}{(\sum_i \beta)^2} \]  

(4.4)

Using the Cauchy Inequality and noticing \( \beta-1 > 0 \), we have \( w_2'(\beta) > 0 \).

So \( w_2(\beta) \) is a strictly monotone increasing function of \( \beta \).

Using the given condition: \( R_c < \exp\left(-c(\tau)\frac{t_0}{\sum_i} \right) \), we have
\[
\lim_{\beta \to 1} w_2(\beta) = -\ln W - \ln (\Sigma z_i) < 0
\]
and
\[
\lim_{\beta \to \infty} w_2(\beta) = +\infty > 0.
\]
So there exists a unique \( \beta_0 > 1 \) such that \( w_2(\beta_0) = 0 \) and
\[ w_2(\beta) < 0 \text{ when } \beta < \beta_0; \quad w_2(\beta) > 0 \text{ when } \beta > \beta_0. \]
But \( w_1'(\beta) = -\frac{w_2(\beta)}{\beta - 1} \), so the same conclusions hold for \( w_1'(\beta) \) for \( \beta > 1 \).
Therefore, \( w_1(\beta) \) attains a minimum at \( \beta_0 \). Hence \( w(\beta) = \exp(w_1(\beta)) \)
attains a minimum at \( \beta_0 \). That is,
\[
\frac{T_c(\beta)}{t_m} \geq w(\beta) \geq w(\beta_0) = \left( \frac{-\ln Rc}{c(\tau)} \sum \frac{\beta_0}{\beta} \right)^{1/(\beta_0 - 1)}.
\]
Therefore we have: \( \frac{T_c(\beta)}{t_m} \geq \left( -\ln(\ln c(\tau)) \right)^{1/(\beta_0 - 1)} \), for all \( \beta > 1 \).

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